UTTRI

Research Report

TTS 2.0
Final Report

Transportation Tomorrow Survey

Siva Srikukenthiran, Patrick Loa, Sanjana Hossain, Brittany Chung, Khandker Nurul Habib, and Eric J. Miller

December 2018

Final Report

2018-12-19

Transportation Tomorrow Survey 2.0

Correspondence:
khandker.nurulhabib@utoronto.ca

Siva Srikukenthiran, Patrick Loa, Sanjana Hossain, Brittany Chung
Khandker Nurul Habib & Eric J. Miller

EXECUTIVE SUMMARY

Background: Household travel surveys are a mainstay of passenger travel demand data collection, relied upon to understand how people use transportation infrastructure and a basis upon which to construct travel demand models. In the Greater Golden Horseshoe (GGH), the regional Transportation Tomorrow Survey (TTS) has been conducted every 5 years since 1986. As one of the largest household travel surveys in the world, the TTS surveys 5% (in excess of 150, 000) of households in the region. The introduction of new forms of communications, particularly cell phones, and the rapid emergence of cell-phone only (CPO) households has raised questions about the reliability of the collected survey data which has relied on the use of a landline-telephone sample frame in the past.

Goals: TTS 2.0 was created with the aim of developing the next generation of travel survey methods for the region to overcome current and foreseeable challenges the TTS has or may face. TTS 2.0 was centred on the investigation of four primary survey modes: phone, web, smartphone and passive methods. Investigation into these modes proceeded first with a literature review report, providing information on the current state of the art in collection methodology for each mode, and providing recommendations for potential small-scale field tests that should be conducted in the next phase. This was followed by a series of smaller focussed research reports, the development of a web-survey platform (TRAISI) for use in later pilots, and a field test around the technical feasibility of smart phones and smartphone survey apps. The main field tests were conducted in the final year, encompassing both sampling and mode investigations. This report acts as a summary and synthesis of these in-depth reports. Key findings and recommendations for the 2021 TTS are presented that emerged from the literature review, pilots and field tests of the TTS 2.0 research programme.

The Core-Satellite Data Collection Framework: The core-satellite framework is a systematic methodology for handling the broad range of travel demand data, needed as travel demand models become more detailed and complicated. It takes into account the need to consider the burden placed on individual survey respondents, declining response rates, particularly for certain population subgroups, and issues fusing data collected by different methods.

A few versions of the framework have been developed over the years, but generally, consist of a core survey and associated satellite surveys. Core surveys are large-sample surveys that collect key demographic and travel behaviour information about respondents that are essential for policy and planning. These surveys are stable over time, usually collecting the same data each iteration with minimal changes in between to maximize comparability. They are conducted frequently or even continuously and are kept short to minimize burden and costs. The current TTS plays the role of the core survey. Satellite surveys are smaller and more focussed with the goal of collecting detailed information on specific aspects or populations. These surveys address information that are not collected in the core survey; however, they need some method to statistically link these data to those collected by the core.

Given issues found in conducting the core TTS over the last decade, and the need for expanded data, this framework was expanded to consist of several parts. Core extension surveys collect additional core data at lower sampling rates than the core and are generally conducted at the end of the core survey. Core-filling surveys aim to address demographic or geographic gaps, or under-representation present in the core data set, and use non-household-based frames. Linked satellites are follow-up surveys conducted after the core that collect additional data about certain sub-populations; as a key trait, they sample from the already surveyed respondents. Independent satellites collect data beyond the core for certain subpopulations but do not have an explicit link to the core dataset, with sampling done independently of the core survey. Finally, passive data are those collected often without the knowledge of those being observed, and usually without a specific travel demand measurement intent. These data are often available only in aggregate form but are collected at much larger sample rates than a survey, while often being collected continuously throughout the year.

The conduct of each of these survey types vary; recommendations on the various aspects of survey design and execution necessary to implement the framework are now summarized.

Sample Frames: Owing to the growing incomprehensiveness of the landline frame, the core survey of the 2021 TTS should adopt an address-based multi-frame sampling approach. The frames used should comprise of address & phone (landline), address-only and phone-only frames similar to the 2016 TTS. The phone-only sample frame can be derived from random digit dialing and verified cell phone listings. To improve the response rate of the frame, pre-notification by SMS can be considered.

Core extension surveys should use the same sample frame as that of the core. On the other hand, core-filling satellite surveys should be based on address-based frames or company/institutional frames, depending on their end goal. Address-based frames would be preferred if the aim of the core-filling survey is to reduce geographical gaps, whereas company/institutional frames would be ideal for reducing demographic gaps. For example, the post-secondary StudentMoveTO survey can be used for improving the representation of student-aged respondents (particularly those living on campus) and the inverted frame can be used to target specific businesses with underrepresented demographics, or underrepresented geographic areas.

In terms of the other satellites, linked satellites should use panel-based frames constructed from the core sample, similar to the core extension survey. As for the independent satellites, frame selection would vary depending on the survey purpose.

Sample Methods: Based on the critical review of different sampling methods, the following recommendations can be made with respect to the sampling methods for the different components of the 2021 TTS. A geographically stratified random sampling technique should be adopted for the core survey. It would be best to retain the current repeated cross-sectional nature rather than shifting to continuous data collection. Respondents for the core-extension survey should be sampled from the core sample according to a predefined sampling rate using the simple random stratified sampling method. Linked satellites should randomly sample potential respondents who belong to the targeted group using the list of individuals who showed interest to participate in future surveys. Finally, depending on the type of population to be surveyed, a choice-based sampling method may be more appropriate for independent satellite surveys, such as active mode or transit on-board surveys.

Sample Size: For the core survey, the current sample size of 5% of the population is recommended. As the core-filling surveys generally employ cluster sampling (with full-institution email-outs), setting sample size is less of a concern than the method to fuse their data with those of the core survey. Since the core-extension survey will randomly sample from the core sample, its sample size will be a fraction of the overall core sample. The exact sample size of this survey will be determined by the specific travel data to be collected and its application, and the size required to derive statistically useful conclusions.

Sample Recruitment: For the multi-frame core survey of the 2021 TTS, it is recommended that households from the landline and address-based frames are recruited through advanced/pre-notification letter, whereas the cell phone-based sample is recruited through advanced texting. Respondents for the core-extension survey may be introduced to the survey immediately after the completion of the core questions. For the core-filling satellite survey, recruitment can be done using the email list available with the institution; on-site recruitment can also be helpful in this regard. On the other hand, for the linked satellites, recruitment should be done using the email or phone list of core respondents who showed interest to participate in future surveys. Independent surveys can adopt innovative and emerging recruitment techniques like roadside intercept and crowdsourcing. Incentives should not be included in the core survey, as it may cause self-selection bias in the sample; however, they can be considered for satellite surveys if the respondent burden is considerably higher.

Survey Mode Selection: There are several survey modes possible for travel surveys: telephone (CATI), web (CAWI), in-person (CAPI) and smartphone. While each individual mode has both strengths and weaknesses, analysis of both the literature and field test results have made clear that a single survey mode is not sufficient for large-scale travel surveys like the TTS. Ideally, respondents should also be provided with the choice of their preferred mode of response, and be able to seamlessly switch between modes. This does, however, present challenges to harmonize biases present in each mode, while maintaining consistent terminology between various surveys.

For the core 2021 TTS, two main modes are recommended (CATI and CAWI). These two modes cover feasible response modes for all household-based frames of the core survey. CAPI is also an option if in-person supplemental surveys are deemed necessary to fill geographic gaps based on results of the initial core survey. These 3 modes are compatible to allow for a multi-mode approach not only for the core survey but core-extension and core-filling surveys, and both linked and independent satellites. To harmonize biases and maximize semantic compatibility, both within the same core survey and between different surveys of the framework, a common platform would be recommended. This would have an added benefit of facilitating data fusion of information collected across the modes.

Smartphone-based collection is not, however, recommended for the core survey at this time, with passive multi-day data collection not yet ready for widespread use, for a variety of technical and population representation issues. Smartphone-based multi-day collection does have its place in smaller linked or independent satellites, for focussed studies on multi-day travel where detailed route traces are desired.

Passive Data: With the current state of available passive data, concrete recommendations on the use of passive data are not currently possible. While there is great potential in using passive data for a variety of purposes, most available sources in the TTS region are not yet matured. As a result, the level to which their potential will be realized and the mechanisms to fuse their data with those from the TTS is unclear; recommendations are therefore premature at this point. For example, PRESTO has yet to be fully implemented in the region leading to uneven penetration, with the current older implementation not yet at a stage where reliable travel demand data could be extracted. Implementation issues include lack of GPS location, minute instead of second-based timestamps and an abundance of unlinked (i.e. one-way) trips that prevent determination of destination given the tap-on only systems used by most agencies. This might change with proposed plans, namely full PRESTO fare media to allow for complete penetration, GPS-enabled devices, and postal code FSA becoming available for registered users.

Data Fusion and Compatibility: An important feature of the core-satellite approach to data collection is merging the fractional information obtained from disparate sets of data to provide a more complete image of the travel behavior of the population. The success of the paradigm depends on effective data fusion. Data fusion in-turn is dependent on maximizing compatibility of data sets prior to fusion. Part of this is handled by the core-satellite framework, which ensures linkage of key variables. Also important are semantic (definitions and wording) and spatial compatibility. A framework was devised to provide direction towards appropriate methods based on the fusion context and indicate areas for further study. The method of fusion is context dependent on the survey data being fused and are divided into three main types: direct matching/record linkage, statistical matching using imputation and modeling techniques, and the creation of a synthetic population having observed travel behaviour.

TRAISI: The core-satellite approach is an acknowledgement of the need to undertake many surveys in order to achieve a representative and in-depth picture of travel demand, and a framework to do so in a coherent and connected fashion. Without a carefully designed survey system what could result is a collection of disparate surveys with data that are difficult to fuse. To these ends, a survey design and execution platform, the TRavel and Activity Integrated Survey Instrument (TRAISI) was conceptualized. TRAISI aims to fill a need for a practical way to conduct core-satellite surveys in the immediate, and eventually act as a data fusion, retrieval, and analysis platform. While an initial version of TRAISI was developed in order to conduct the field tests of the TTS 2.0 project, the subsequent version of TRAISI is meant to be a true core-satellite platform. It includes features not contained in traditional survey systems for this purpose, namely deep integration of multiple survey modes and survey mode hybrids, and fulfilling semantic compatibility needs for data fusion. An initial implementation of this more ambitious framework was constructed, built using the latest web technologies and using an architecture consisting of a central web server accessible via an API and web applications to design and take surveys. This architecture allows for the platform to progressively gain functionality, for example, to allow for live assistance for respondents, analysis of survey data and for external data sources (e.g. smart-card) to have end points to transfer data.

2021 TTS Questionnaire: In addition to methodological recommendations, also recommended are modifications to current TTS questions and additional questions. Modifications include greater granulation of household income categories, occupations and trip purpose, as well as a reduction of the minimum age to collect trip information from 11 to 6 years old. These changes would bring the data collected by the TTS in-line with the census and other Canadian travel surveys, and provide the detail needed for modern activity-based models. Additional recommended questions include housing tenure, residence duration, vehicle information, kinship and indicating household members and vehicle usage on trips. These are primarily aimed at collecting household interaction data currently omitted from the TTS and to make possible auto-copying of trips between household members to reduce respondent burden. The use of a platform like TRAISI should enable these expanded questions while minimizing impact on respondent burden.

Future Trends in Survey Design and TTS Research: The recommendations in this report, while a strong departure from the 2011 TTS, build on the large changes made for the 2016 TTS, aiming to both refine them by providing guidance to improve execution, and place this multi-pronged methodology within a formal survey collection architecture. This architecture is future-facing given the clear pattern emerging that a core TTS survey will be progressively less complete and require additional surveys to feed data-heavy modelling methods.

In part, this conservative approach is meant to ensure that data from subsequent TTS can be comparable while allowing for flexibility of approach and collection. This is necessary to both make up for any data or coverage deficiencies as well as allow for testing and incorporating emerging data sources. The recommended core-satellite structure enables this type of exploration through the use of linked or independent satellites that have the flexibility to experiment with new methods.

There are some key trends worth highlighting that are expected for future TTS. First are the continued expansion and availability of passive data sources for continuous observation and measurement of travel demand. How they fit in understanding travel patterns will be heavily dependent on penetration rates, device upgrades to provide required data and the ability of researchers to solve some fundamental technical issues. Next, survey modes are expected to continue to evolve as call-based methods become progressively more difficult to execute, resulting in a shift towards web and smartphone methods. This is dependent on smartphone apps continuing to improve (both technically and in their acceptance by the public), and the development of TRAISI to improve CAWI methods and integrate data from all modes.

Finally, handling data from these many sources will require a shift in the data management model currently used for TTS from purely data collection/management to also providing standardized integration of modelling methods for non-academic end-users. This will be required for proper application of data fusion techniques to eventually allow for accurate synthetic populations to be generated that take into account all input sources simultaneously.

While significant work was performed across many areas within travel demand data collection in the course of the TTS 2.0 project, given the trends described, a continuous research effort is needed to progressively evolve the TTS over time. Part of this effort should be to deal with how to exploit and integrate data sources from emerging technologies, particularly methods of data fusion. Also critical are improvements to methods to recruit and encourage participation; while predominantly a marketing task, it is critical to convince the public of the importance of the TTS to improve response and completion rates, as well as data quality.

Final Report

TRANSPORTATION TOMORROW SURVEY 2.0

Table of Contents

Glossary of Terms

Term	Description
AADBT	Average Annual Daily Bicycle Traffic
API	Application Programming Interface
CANSIM	Canadian Socio-Economic Information Management System
CAPI	Computer-Assisted Personal Interview
CATI	Computer-Assisted Telephone Interview
CAWI	Computer-Assisted Web Interview
CDR	Call Detail Record (recorded by cell phone towers upon cell phone events)
Complementary Datasets	All other data collected that could potentially be used to understand travel or act as verification/validation data but are not linkable to the core-satellite data
Core Survey	Large-scale population-wide high-sample-rate survey collecting key data
Core-Extension Survey	Follow-up survey of a sample of core respondents asking additional core survey questions.
Core-Filling Survey	Survey asking at least the same questions as the core survey but targeted at a geographic or demographic gap of the core survey
CUTA	Canadian Urban Transit Association
Data Fusion	Process of integrating data from two or more sources into a single data set through common variables
DMG	Data Management Group (manager of TTS data)
DMV	Department of Motor Vehicles
FMS	Future Mobility Survey
GGH	Greater Golden Horseshoe
Goulias Core-Satellite Framework	Original core-satellite framework by Goulias et al (2011) upon which the TTS 2.0 core-satellite framework is built
GIS	Geographic Information System
GPS	Global Positioning System
GSM	Global System for Mobile Communications
GTFS	General Transit Feed Specification
HTS	Household Travel Survey

Independent Satellite Survey	Survey conducted independent of the core-survey with a new respondent sample of the population; must collect some key core-survey linkage variables
ITS	Individual Travel Survey
Linked Satellite Survey	Follow-up survey of a focussed subset of core survey respondents asking non-core questions
MAC	Machine Access Control
Mail-Back Questionnaire	A paper questionnaire that is meant for respondents to complete at their leisure before mailing back to the survey administrators
MTMC	Mobility and Transport Micro Census
Multi-Modal Survey	A survey conducted using multiple survey modes
NCHRP	National Cooperative Highway Research Program
NHTS	National Household Travel Survey
OD	Origin-Destination
Passive Data	Data collected usually at a large sample rate generally for non-travel demand data reasons but provide a data on travel behaviour
Passenger Travel	Trips made by residents within the GGH region
Passenger Travel Data	Information that can be used to characterize or understand passenger travel behaviour
Satellite Survey	Small-scale possibly population or activity-specific survey
SHANTI	Survey Harmonization with New Technologies Improvement
SP	Stated Preference
StatCan	Statistics Canada
Survey Mode	The method(s) through which data are collected for a survey
TRAISI	Travel and Activity Integrated Survey Instrument – Survey platform developed for TTS 2.0

1 INTRODUCTION

Household travel surveys are a mainstay of passenger travel demand data collection, relied upon to understand how people use transportation infrastructure and a basis upon which to construct travel demand models. In the Greater Golden Horseshoe (GGH), the regional Transportation Tomorrow Survey (TTS) has been conducted every 5 years since 1986. As one of the largest household travel surveys in the world, the TTS surveys 5% (in excess of 150, 000) of households in the region. Until recently, it was an extremely successful method for efficiently gathering standardized, high-quality travel information on the residents of the region, relying upon the landline telephone directory as its sole sample frame. The introduction, however, of new forms of communications, particularly cell phones, and the rapid emergence of cell-phone only (CPO) households has raised questions about relying on the landline directory as the only sample frame.

In response to these developments, a series of studies were conducted by the study team into current and emerging challenges in conducting passenger travel surveys. These included a 2008 study of GGH transportation data needs, current practice, and recommendations for improving data collection methods, and a follow up report commissioned by the Transportation Association of Canada (TAC) into urban passenger travel data collection methods and needs. This TAC report, presenting a recommended framework of collection, formed the basis of the TTS 2.0 project, conducted from April 2015 to December 2018. TTS 2.0 was created with the aim of developing the next generation of travel survey methods for the region to overcome current and foreseeable challenges the TTS has or may face.

1.1 Goals of TTS 2.0 and this Report

The TTS 2.0 was constructed around 3 major components:

- ***Methodological research*** to clarify the state of the art in various aspects of travel data collection methods, and investigate and address technical issues
- ***Field testing*** of promising data collection methods to examine efficacy and practicality in the GGH context
- ***Design*** of the recommended TTS 2.0 data collection and management program for implementation post-2018

All 3 components were originally centred on the investigation of four primary survey modes: phone, web, smartphone and passive methods. Investigation into these modes proceeded first with a literature review report, providing information on the current state of the art in collection methodology for each mode, and providing recommendations for potential small-scale field tests that should be conducted in the next phase. This was followed by a series of smaller focussed research reports, the development of a web-survey platform (TRAISI) for use in later pilots, and a field test around the technical feasibility of smart phones and smartphone survey apps. The main field tests were conducted in the final year, encompassing both sampling and mode investigations. A full list of all reports is provided in Table 1.

Table 1-1 List of TTS 2.0 Reports

Report Name	Year Produced	Code in this Report
Current State of Landline Survey Methods	2015	Landline
Current State of Smartphone Survey Methods	2015	Smartphone
Current State of Web Based Survey Methods	2015	Web

Continuous Travel Surveys	2015	Continuous
Issues of Sample Size	2015	Sample Size
Passive Data	2016	Passive
Sample Frame	2016	Sample Frame
Smartphone Technical Test	2016	Smartphone Technical
Web Survey Design	2016	Web Design
Multiple Sample Frames (2016 TTS Analysis)	2017	Multiple Frames
Core-Satellite	2017	Core Satellite
Data Fusion	2017	Data Fusion
In-Person Survey Field Test	2017	In-Person Field
Web Survey Field Tests	2017	Web Field
Smartphone Field Test	2018	Smartphone Field
Inverted Sampling Method	2018	Inverted Field
Preliminary Investigation of using PRESTO Data	2018	PRESTO
This Final Report	2018	Final

This report acts as a summary and synthesis of these in-depth reports. Key findings and recommendations are presented that emerged from the literature review, pilots and field tests of the TTS 2.0 research programme. These are centred on the presentation of the main data collection paradigm being advised for household travel data collection both in general and specifically for the 2021 TTS. References to relevant sections in the other reports are provided for further reading, using codes listed in Table 1-1, with specific references to sources contained mainly within these referred reports.

Overall, the goals of this report are as follows:

- Provide a conceptual summary of key information and conclusions discovered and developed in the collection of prior TTS 2.0 reports, organized under several key themes.
- Recommend a data collection paradigm or framework for transportation demand data to:
  - Provide prescriptive methods for the various stages of undertaking a survey.
  - Note gaps that remain to be answered.
- Provide specific recommendations for the 2021 TTS.
- Provide a longer-term vision for continued improvement to the data collection paradigm.

1.2 Reading this Report

This report is aimed towards a variety of readers with an interest in passenger travel surveys, and in particular household travel surveys. Users groups considered are agency officials, consultants, and researchers, with use cases ranging from those designing and conducting surveys to those contracting out and managing survey data.

The report is divided up into 8 major sections, dealing with different areas of passenger travel demand collection, the pertinence of which will depend on the intended use case.

Section 2 (Transportation Data) provides an overview of the pool of data that can or needs to be collected in order to understand travel behaviour. This section includes an overview of data currently collected by household travel surveys in North America and Europe. This section will be useful for those less familiar with the area, or those searching for inspiration for data that should be collected in a travel survey based on what has been collected in similar efforts.

Section 3 (Core-Satellite Collection Paradigm) acts as the main framework section of the report, providing a description of the central data collection paradigm proposed for passenger travel surveys. This section defines the paradigm's components and acts as a roadmap for the remainder of the report. Because of this broad focus, this section is recommended for all readers, regardless of the specific survey task or use case.

Sections 4-6 cover survey execution details, most applicable to agency officials during an RFP process when determining contract specifications and evaluating proposals, and agency officials, consultants, and researchers directly carrying out travel surveys. **Section 4** (Sampling Frames and Methods) provides a critique of the various sampling frames in terms of the relevant population type, source of acquiring frame lists and their associated strengths and weaknesses. It also includes a discussion of sampling methods, sample size requirements, and sample recruitment and incentives. **Section 5** (Survey Mode Selection) critiques each survey mode (pros and cons, associated sampling frames, general respondent profiles, applicability, and typical applications). It focusses on the 4 key modes: computer-aided telephone interview, web, smartphone and in-person. Finally, **Section 6** (Designing to Minimize Biases) provides proactive ways to minimize survey biases in 4 key areas: survey mode, respondent fatigue, non-response, and proxy.

Collecting data via several surveys or passive sources under the core-satellite framework necessitates having a method to ensure data compatibility and a framework in place to fuse the final data. **Section 7** (Data Fusion and Compatibility) summarizes and discusses various approaches to data fusion, including applications of several methods of fusion. It includes a critique of passive data sources with respect to their ability to supplement or replace conventional survey collection methods. While this report does not provide a definitive guide for fusion, this section does describe a general framework for fusing disparate sets of data collected under the core-satellite collection paradigm. It also provides a roadmap for work needed to handle the rapidly evolving passive data sources in the region. This section is aimed at all end users of collected survey data.

A key part of data compatibility is consistency in both the terminology of and the design used by the collection instrument. This ensures that any biases with respect to the collection method are standardized between data collection in various surveys, an important consideration for a core-satellite collection system. As such, **Section 8** provides an overview of the Travel Internet Survey Interface (TRAISI). TRAISI is a CATI/CAWI hybrid system to design, execute and evaluate travel surveys of various types. Features in TRAISI that assist in the execution of the core-satellite data collection paradigm are provided in this section.

Finally, **Section 9** (Final Recommendations & Future Directions) presents the recommendations for the 2021 TTS and future research and development expected at the conclusion of the TTS 2.0 project. The latter includes an overview of new developments and initiatives being tested around world, highlighting the need to concurrently pilot test new methods in conjunction with future TTS.

2 TRANSPORTATION DATA

The time and resources dedicated to the collection of transportation data are directly related to the value that data bring to the transportation planning and decision-making process. The value of data lies in their ability to provide a reflection of the real world. In the context of travel surveys, transportation data help to paint a picture of how the members of the target population utilize and interact with the transportation network in their municipality or region. Additionally, the collection of these data also facilitates the creation of models which can be used to forecast future travel demand. Taken together, these applications demonstrate that the collection of transportation data has the potential to create a basis for evidence-based planning and decision-making. In an era of budgetary constraints and politically motivated infrastructure projects, data collected through household travel surveys (HTS) like the TTS can be used provide an objective estimate of the impact that a project could have on the surrounding area. The caveat is that these data must provide an adequate representation of the members of its target population if they are to be used to understand or forecast demand.

In recent iterations of the TTS, the ability to achieve this goal has been hampered a number of factors; in addition, emerging data sources and changing trends in the use of data has led to the need to rethink what and how data are collected. In order to address the obsolescence of the current survey structure, it is crucial to understand and identify the different types of data that pertain to travel. In advance of re-designing a passenger travel data collection paradigm for the modern era, one needs to carefully consider the domain of travel critical for infrastructure planning and operational policies. The 2012 TAC report [**TAC P6, 3.0**] provides a high-level characterization of the urban system and how transportation interacts with the various components of an urban area. This report also highlights the importance of collecting transportation data, identifies the main users of these data, and presents and categorizes the different aspects of travel demand. This section looks to expand on this prior work by specifically addressing the travel behaviour, travel data, users, and data applications relevant to devising a flexible and adaptable collection framework. The section concludes with an analysis of the current scope of data collected by the TTS, evaluating potential modifications and expansions that would better align it with expected future travel behaviour and data use requirements.

2.1 The Universe of Passenger Travel Behaviour

The term passenger travel has multiple meanings. For some, it refers to visiting a place where they do not usually reside. For others, it involves movement between places in their region. As Figure 2-1 shows, travel demand can be broken down into several components. The combination of different trip-makers, trip purposes, and trip characteristics (i.e. the 'who', 'why', 'where', 'when', and 'how' of travel demand described in Figure 2-1) are what constitute the universe of travel behaviour. Because the goal of the TTS is primarily to help understand and forecast travel demand within the region (i.e. the GGH), the focus of this project are data that could be used to describe intra-regional passenger travel. Consequently, the term "passenger travel" refers to trips made by residents within the GGH region.

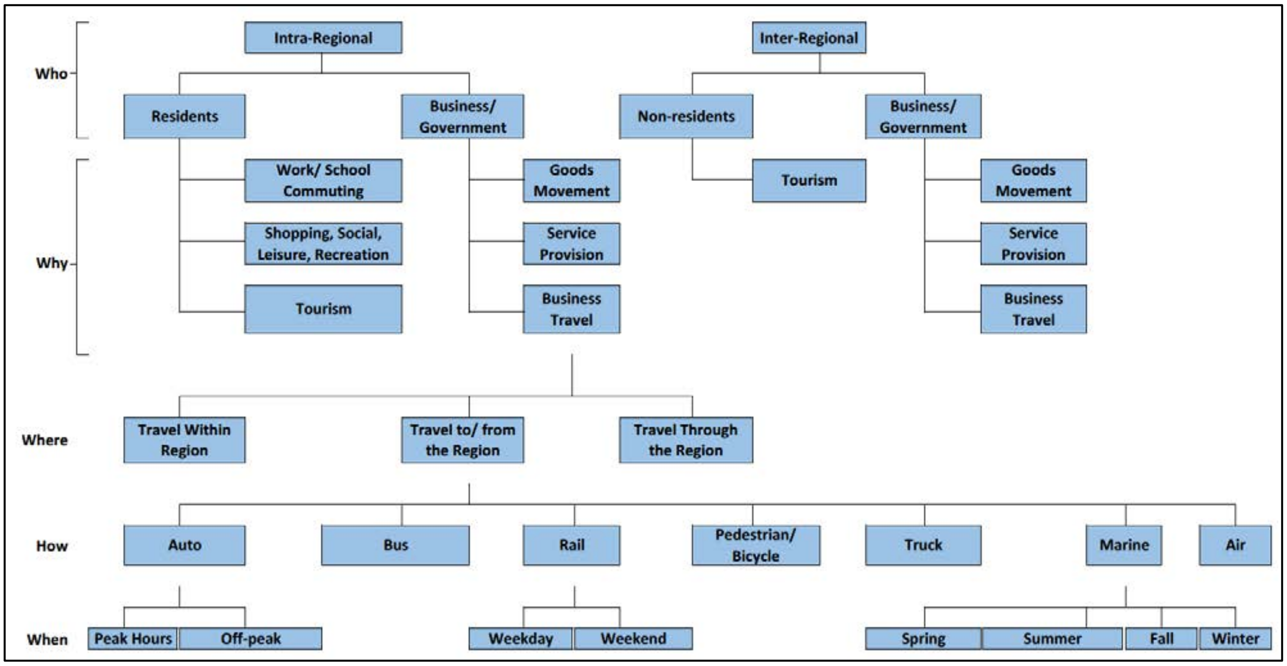

Figure 2-1: Components of Travel Demand (Source: Adapted from Roorda and Shalaby, 2008)

2.2 Passenger Travel Data

Passenger travel data refers to information that can be used to characterize or understand passenger travel behaviour. It is important to understand that data collection can be classified in multiple ways based on the specific approach taken to collect data, i.e. household-based surveys, other types of surveys, and alternative forms of data [**TAC P6, 4.0**]. On the other hand, data collection methods can also be classified based on the level of involvement on the part of the respondents, i.e. active surveys, passive data collection, hybrid methods, proactive data provision, and administrative datasets. Here, data collection methods are classified into one of three categories: household surveys, other active data collection, and passive sources. The goal of this section is to provide a comprehensive list of passenger travel data that are currently collected. Understanding the types of information that are considered relevant to the understanding of passenger travel behaviour is critical when reimagining a new data collection paradigm.

2.2.1 Household Travel Surveys

A 'survey of surveys' was conducted to identify information that is typically collected through household travel surveys. HTS examined were those conducted in regions or municipalities in Canada, due to their contextual similarities to the TTS, and those conducted in large municipalities or regions abroad; manuals pertaining to the design of travel surveys were also consulted. In total, 11 household travel surveys were reviewed along with two survey design manuals:

- **Surveys in Canada:** Greater Golden Horseshoe, Toronto, National Capital Region, Saskatoon, Montreal, Edmonton, Metro Vancouver, Calgary
- **Surveys outside Canada:** Various studies in United States (e.g. Utah), London (UK)
- Survey design manuals: the NCHRP, SHANTI

The results of this survey are broken down into three components: household attributes, individual attributes, and trip information. This section identifies the information that a household travel survey typically collects for each of these categories and provides examples of how this information is used in practice.

2.2.1.1 HOUSEHOLD ATTRIBUTES

When a travel survey is conducted at the household level, it is common for information on household characteristics and household composition to be collected. The *basic* set of information that was collected in each of the 11 surveys are:

- Home address
- Type of dwelling unit (e.g. single-detached, semi-detached, apartment, condo, townhouse)
- Household size
- Income
- Number of vehicles available for personal use

Some surveys also solicit detailed information pertaining to vehicle ownership (e.g. make, model, year, fuel type, etc.) and relationships between household members. This practice is more prevalent outside of Canada than it is within Canada. Household attributes have been used to support the development of trip generation models, car allocation models, activity scheduling models, and emissions models.

2.2.1.2 INDIVIDUAL ATTRIBUTES

Individual attributes play a crucial role in supporting the modelling applications that are facilitated by survey data. The most basic individual attributes pertain to demographics. The age and gender of respondents are often collected, while race, disability issues, and education level tend to be less common. Demographic information plays an important role in determining the extent to which the sample represents the target population, and are often used to facilitate data expansion. It is also common to ask respondents to identify the mobility tools that they have at their disposal. Almost all of the reviewed HTS collect information on driver's license ownership. On the other hand, collecting information on transit pass ownership tends to be seen in surveys that focus on a more local (i.e. municipal or regional) context. In response to technological shifts, collecting information on enrollment in car-sharing services has become a more common practice in recent years. Information on the access that each respondent has to various mobility tools is often used to support mode choice modelling by helping to define the choice set of each respondent.

In addition, some surveys also collect information on the "typical" attributes of a respondent's travel. Examples of this type of information include the usual time and mode of a respondent's commute, or the usual fare payment method used when taking transit. This type of information is collected by the National Household Travel Survey (NHTS) conducted in the U.S. and has also been seen in travel surveys conducted in Edmonton, Vancouver, and Utah. This type of information is typically used to support the development of more advanced mode choice models. Because of their impact on travel behaviour, many household travel surveys also collect information on employment and student status. Some surveys also collect information on the type of occupation and the extent and flexibility of the employment or school hours of each respondent. This information is often used to determine trip rates and to facilitate the estimation of mode choice models. Some household travel surveys will also solicit information on establishment characteristics, such as the location of one's school or place of employment, the availability of free parking at work, or vehicle ownership requirements imposed by one's employer.

2.2.1.3 TRIP INFORMATION

The most critical aspect collected by an HTS are trip information. This portion of the survey will typically ask respondents to indicate, for each trip, the time at which they depart from the origin, the time at which they arrive at the destination, the modes that they used, and if applicable, the reason that a respondent did not make a trip on the date in question. Some household travel surveys take this a step further and ask respondents to provide detailed information specific to the use of an automobile or transit. This information is used for a wide range of applications, including the generation of origin-destination matrices, the determination of a peak hour factor, and the understanding and forecasting of travel demand.

The collection of trip information requires that two key decisions be made – the minimum age for trip reporting, and the number of days for which trip information will be reported. Among the surveys that were reviewed, many collect trip information for household members aged five or older. For the TTS, this threshold is set at 11 years of age, while the London household travel survey set its threshold at 15 years of age; the Utah travel survey does not set a minimum age requirement. Most of the reviewed travel surveys collect information for a single weekday. Notable exceptions are surveys conducted in the Metro Vancouver Area, which collect trip information for four days, and some surveys in Toronto, the U.S., and Europe (Germany, Italy, and Spain) which collect trip information for both weekdays and weekends.

The Mobility and Transport Microcensus (MTMC), conducted in Switzerland, collects trip information in an extraordinary amount of detail. Most travel surveys will ask respondents for the origins and destinations of their trips, the modes they used to travel, and the purpose of each trip. The MTMC goes one step further and asks respondents to provide additional information about their trips. Administered via computer-assisted telephone interview (CATI), the MTMC collects information such as (Ohnmacht, et al., 2012):

- The weight of each respondent
- The type of recreational activity (when a respondent reports a recreational trip)
- The type of purchases made (when a respondent reports a shopping trip)
- The number of stores visited (when a respondent reports a shopping trip)
- The reason(s) that the respondent had for accompanying another person on one of their trips
- The items carried during their trip
- Their motivation for using active modes
- The availability of bicycle parking at the destination of a given trip

2.2.2 Other Active Data Sources

Although household travel surveys form the basis of transportation data, they often need to be supplemented by data from other sources. Within the Canadian context, sources of data that have potential relevance include:

- Non-household travel surveys
- The Canadian Census
- Other federal datasets (both StatCan and non-StatCan)
- Provincial datasets
- Municipal datasets
- Data collected by non-government associations
- Commercial (private sector) datasets
- Open-source datasets

A detailed description of these sources of data can be found in **[TAC P4]**. It is important to note that in Canada there is often a cost associated with gaining access to a dataset, meaning that purchasing all the supplemental data required for a certain application may be costly.

An emerging source of active data is the smartphone survey. The use of smartphone surveys allows key information to be reported by respondents while additional information (such as trips, trip purpose, mode of travel, etc.) can be obtained either through inference or by asking respondents additional questions. The ability of smartphone traces to provide information such as travel paths, acceleration and deceleration, and link-level speeds without imposing an excessive amount of survey burden on respondents has helped increase the popularity of this survey mode.

2.2.2.1 NON-HOUSEHOLD TRAVEL SURVEYS

This section provides a profile of several travel surveys that are not administered at the household level. Each profile includes a description of the survey, the frequency, and prominence of its conduct in Canada, and a brief description of the type of data collected by the survey and its applications. The frequency and prominence of the conduct of each survey in Canada is based on the results of a survey of Canadian transportation agencies regarding their transportation data collection practices, conducted from March to April of 2012 by the Transportation Association of Canada (TAC). For more details about this survey, see **[TAC P5]**.

2.2.2.1.1 Place of Employment Surveys[1]

Description: Place of employment surveys obtain information on trips made to or from business establishments, specifically the number and types of trips attracted to these establishments. This type of survey is typically conducted in one of four ways: an intercept survey of persons entering or leaving an establishment, a centralized employee survey, an intercept survey of visitors, or a hybrid of the centralized employee and visitor intercept survey. Place of employment surveys are administered using paper questionnaires, computer-assisted interviews, web surveys, and pen-and-paper interviews.

Frequency and Prominence in Canada: A majority of agencies in Canada (two-thirds) utilize this type of survey, generally relying on third-party surveys. They are done both as one-offs or repeated every five years.

Data Collected: The data that are collected by place of employment surveys will vary based on the nature of the survey. Five approaches to data collection exist: employer surveys, employee surveys, visitor surveys, person and/or vehicle counts, and surveys and/or counts of delivery persons. The categories of information solicited by this type of survey include:

- Establishment information: Name of employer, key manager, location, telephone numbers, type of business, employees, site size, volume of business, parking availability, parking policies, transit availability, bicycle and pedestrian amenities, employer TDM measures
- Employee information: Travel to and from the establishment, address of trip origin and destination, type of place or land use of origin and destination, start and end time of trips, travel group size for each trip, travel mode for each trip, parking information for each trip to establishment, personal information about employee, household information from employee, attitudinal and SP questions
- Visitor information: Address of trip origin and destination, type of place or land use of trip ends, address of trip end, start and end time of trip, travel group size for each trip, travel mode for the trip, parking info, specific trip purpose

[1] Adapted from (Southworth, et al., 2010) unless otherwise specified

When a place of employment survey is conducted as an intercept survey, counts of persons entering and/or exiting the building must also be taken, to facilitate data expansion.

Use Cases: Trip attraction rates that are derived from place of employment surveys are typically used to support the study of re-zoning, traffic impact studies, and the development of congestion management and trip reduction programs.

2.2.2.1.2 Roadside Origin-Destination Surveys

Description: Roadside OD surveys are one of the classical methods of collecting road-based data by intercepting respondents in the midst of travel **[TAC P2, 3.2]**. The goal of this type of survey is to develop an understanding of the types of vehicle trips that utilize specific roadway segments (Everett, et al., 2014). Often these types of surveys are conducted near the boundary of a model study area, to facilitate the development of "external-external and external-internal trip tables for the model" (Everett, et al., 2014). Roadside OD surveys are typically conducted in one of four ways (Everett, et al., 2014):

- <u>License plate surveys:</u> Licence plate numbers are recorded manually or through automated means; these numbers are cross-referenced with those from DMV records, and the owner of the vehicle is sent a mail-back questionnaire
- <u>Roadside handout surveys:</u> Fieldworkers handout mail-back questionnaires to some or all of the drivers passing the survey station
- <u>Roadside interview surveys:</u> Fieldworkers conduct computer-assisted or pen-and-paper interviews with some or all of the drivers passing the survey station
- <u>Combined roadside interview and handout surveys:</u> Fieldworkers stop some or all of the vehicles passing the survey station to conduct short interviews and distribute mail-back questionnaires
-

This survey has traditionally been used to collect origin-destination patterns for auto trips, hence the name "OD survey" **[TAC P2, 3.2]**.

Frequency and Prominence in Canada: The most popular method of obtaining roadside OD data is through the use of a third-party survey, with some agencies commissioning a roadside OD survey, or by conducting it in-house. There appears to be little consistency in the frequency with which this type of survey is conducted.

Data Collected: The data collected through roadside OD surveys typically fall into one of three categories: travel data, demographics, and attitudinal data. For more information on the information collected through roadside OD surveys, see **[TAC P2, 3.2]**.

Use Cases: On their own, the data collected through roadside OD surveys are used to derive metrics pertaining to traffic volumes by vehicle type, tonnes of commodities, trip lengths, and axle weights. These data are also used as an additional source of information to calibrate or validate travel demand models. Additionally, data collected through roadside OD surveys are used update and re-calibrate travel demand models between household travel survey years. (Everett, et al., 2014)

2.2.2.1.3 Transit Onboard/ Stop Surveys

Description: Onboard surveys collect data from transit users by approaching them at transit stations or onboard transit vehicles **[TAC P2, 3.3]**. The conduct of this type of survey has become a standard practice for transit agencies both in Canada and abroad **[TAC P2, 3.3]**. This type of surveys typically conducted in one of three ways (Rousseau, et al., 2011):

- Drivers distribute a mail-back questionnaire
- Surveyors onboard a vehicle conduct interviews with passengers

- Surveyors onboard a vehicle distribute questionnaires to passengers, which can be mailed back or returned to them

Frequency and Prominence in Canada: An overwhelming majority of Canadian agencies conduct these surveys in-house. There is very little consistency in the frequency with which this survey is conducted.

Data Collected: The data collected through transit onboard surveys typically fall into one of three categories [**TAC P2**]:

- Travel data: Boarding and alighting location, stop, or station, trip purpose, arrival and departure time, travel time, origin and destination address, access and egress mode, transit routes used, fare payment type, auto ownership, auto availability for the trip
- Demographics: Household size, occupation, household income, age, gender
- Attitudinal data: Perceptions of transit service, customer satisfaction

Use Cases: The main objective of a transit onboard survey is to support scheduling, operations planning, long-term planning and design, performance analysis, market evaluation, and the determination of summary statistics. The data collected through transit onboard surveys can form the basis of models that can be used to analyze the utilization of new transit lines or facilities. These data can also be used to understand the demographic and ridership profiles of the sampled routes, transfer characteristics, and fare class utilization. (Rousseau, et al., 2011)

2.2.2.1.4 Truck/ Freight/ Commercial Vehicle Surveys

Description: The primary objectives of commercial vehicle surveys are to develop an understanding of the movement of goods and commodities and to understand the characteristics of truck and commercial vehicles. This type of survey is administered using computer-assisted telephone interviews (CATI) and self-administered mail-back surveys. (Southworth, et al., 2011)

Frequency and Prominence in Canada: The use of truck, freight, or commercial vehicle surveys are not a common practice; those who do often commission a consultant to conduct the survey or obtain third-party survey data. This type of survey is conducted most often as a one-time survey but can be repeated on frequent cycles (e.g. annually).

Data Collected: The data that are typically collected through commercial vehicle surveys includes (Southworth, et al., 2011):

- Administrative information: Business or employer location and address, survey location (if applicable)
- Travel information: Ultimate trip origin and destination, interim origins and destinations, start and end time of entire trip
- Route information: Major routes used for travel, frequency of trips using alternative route per period of time, reasons for using alternative routes
- Other: Truck classification, commodity or good being transported, locations for pickups and deliveries (if applicable)

Use Cases: Data on the movements and characteristics of commercial vehicles are used to conduct goods movement studies, to inform goods management systems, and to support studies of freight movements at border crossings. A less common application of data from commercial vehicle surveys is to support the development of travel forecasting models at the state, regional, subarea, and local levels. (Southworth, et al., 2011)

2.2.2.1.5 Bicycle Surveys

Description: These surveys attempt to collect data specifically pertaining to bicycling. Bicycle surveys may aim to address the underrepresentation of cyclists in a household travel survey or to collect detailed information that may not be feasible to collect through a household travel survey. Bicycle surveys can be carried out through intercept surveys, mail-back questionnaires, web surveys, computer-assisted telephone interviews, and smartphone surveys.

Frequency and Prominence in Canada: Bicycle surveys are not common in Canada, and if used are usually not conducted using in-house personnel. There does appear to be a willingness among respondents to utilize this type of data if it were available. This type of survey is generally done infrequently (one-off or every several years).

Data Collected: The data collected through a bicycle survey varies based on the goals of the survey. Examples of the information solicited include:

- The characteristics of the bike trip that a respondent is in the process of completing (for intercept surveys)
- A map of the route taken for a bicycle trip
- Description of changes in cycling behaviour by season
- Respondent demographics
- The duration and distance of cycling trip(s)
- The origin and destinations of cycling trips
- Motivators of and barriers to cycling

In addition to demographic and travel data, attitudinal data may also be collected through this type of survey. Attitudinal information is useful to the study of cycling due to its ability to identify different types of cyclists and their ability to account for the subjective factors associated with bicycle usage (Munoz, et al., 2016)

Use Cases: A fundamental application of bicycle survey data is to gain an understanding of cycling volumes and behaviour. This information can then be used to:

- Identify seasonal variations in usage
- Develop the number and causes of collisions
- Obtain volumes along dedicated facilities
- Understand the demand for and potential economic impacts of new or improved facilities
- Develop or update existing models (e.g. facility choice, route choice, mode choice – i.e. cycling vs. not cycling)
- Estimate average annual daily bicycle traffic (AADBT)
- Support modelling and planning applications

2.2.2.1.6 Pedestrian Surveys

Description: Pedestrian surveys obtain information pertaining to walking trips, either to complement or supplement data collected through household travel surveys. Part of the need for this type of survey stems from the tendency for the non-motorized trips rates collected through travel surveys to be much lower than they are in reality (Victoria Transport Policy Institute, 2017). Pedestrian surveys are often conducted in conjunction with the collection of cycling data; rarely are they conducted on their own. Pedestrian data has often been collected through manual and automated counters; however, newer methods such as video-based detection, smartphone traces, and Bluetooth detection are also used.

Frequency and Prominence in Canada: Pedestrian surveys are not common amongst Canadian agencies. Those who do employ them either conduct their own or use results from third-party surveys. There is, however, a willingness to use this type of data if they were available. There is a lack of consistency in the frequency with which this type of survey is conducted.

Data Collected: Pedestrian surveys often attempt to identify the factors that influence how often a respondent walks and the purpose(s) for which they walk. Examples of information that is collected through pedestrian surveys include:

- Home location
- Work location
- Demographics (age, gender, occupation status, student status) (Center TRT, 2013)
- Time spent per week walking, by trip purpose (Alta Planning + Design, 2015)
- Pedestrian counts
- Frequency of walking (daily, at least weekly, at least monthly, at least annually, never) by trip purpose (Center TRT, 2013)
- Role of different factors in deterring more walking (Center TRT, 2013)
- Perceived value of proposed facility or environmental improvements (Center TRT, 2013)
- Perceived priority of proposed facility or environmental improvements (Alta Planning + Design, 2015)

Use Cases: Examples of the application of pedestrian survey data include: the estimation of mode choice models (i.e. walking or not walking), to study the effects of rainfall on pedestrian volumes, and to support modelling and planning.

2.2.2.1.7 Parking Usage Surveys

Description: Parking usage surveys are often conducted with the intention of studying parking supply and demand, utilization, and turnover within the context of transportation planning. Depending on the location of the parking facility, the survey may be aimed at persons parking at the destination of an automobile trip or at persons for whom the parking lot is a waypoint in their trip. Parking usage surveys have been conducted by (Simon & Simek, 2014):

- Interviewing auto users arriving at or leaving a parking facility;
- Placing mail-back questionnaires on windshields; or
- Recording licence plate numbers and mailing the car owner a questionnaire

Frequency and Prominence in Canada: Parking surveys are fairly common, and generally conducted in-house. There is little regularity in the frequency with which this survey is conducted.

Data Collected: The data collected through parking usage surveys can be broken down into one of five categories (Simon & Simek, 2014):

- Travel information: Trip purpose, arrival time at and/or departure time from the parking facility, payment information (both short- and long-term costs), auto occupancy, home location and land use of destination
- Waypoint trip information: Ultimate trip destination, walking distance and time to reach the destination from the parking facility, mode used to reach ultimate destination
- Demographics: Home location, age, gender, income
- Facility-specific information: Number, type, and geographic distribution of trips attracted to a specific facility, parking facility location, parking facility cost, mix of short- and long-term parking, trips made to and from park-and-ride facilities

- Qualitative information: Perception of difficulty finding parking, strategies used to park at preferred locations

Use Cases: Parking usage surveys have increasingly been used to support travel demand modelling. The data collected through these surveys have assisted the model calibration process by "identifying and matching the demand and supply of vehicle trips generated to and from parking facilities within specific traffic analysis zones (TAZ)". These data can also be used to understand price elasticity for parking costs. (Simon & Simek, 2014)

2.2.2.1.8 Special Traffic Generator Surveys

Description: Special generator surveys are a unique class of survey that are conducted in order to describe travel "to and from special trip generators" (Endemann, et al., 2010). Examples of special generators include hospitals, universities, airports, military bases, and major shopping centres (Mamun, et al., 2010). The irregular nature of arrivals at and departures from these types of establishments means that a typical trip generation model cannot provide a realistic representation of the impacts that a special generator can have on the transportation system (Mamun, et al., 2010). Thus, a survey dedicated to collecting information on these types of locations is necessary. This type of survey may be conducted via the web, or through personal interviews [**2017 Core Satellite, 4.3**].

Frequency and Prominence in Canada: Special traffic generator surveys are somewhat uncommon in Canada. When these data are used by agencies, they tend to be obtained via third-party surveys or through surveys conducted by the agencies themselves. Special traffic generator surveys are often conducted as one-offs or in an irregular manner.

Data Collected: A survey of this nature will typically collect information pertaining to the characteristics of trips made to a special generator. This includes respondent demographics, the origin of the previous, the destination of the next trip, the amount of time that will be spent at the special generator, departure time, arrival time, travel time, and mode of travel [**2017 Core Satellite, 4.3**]. Depending on the nature of the survey, additional questions may also be asked. For example, a post-secondary student survey may ask respondents to complete a travel diary [**2017 Core Satellite, 4.3**].

Use Cases: The application of data collected through special generator surveys typically falls into one of two categories – understanding behaviour and developing models. On their own, these data can be used to understand the travel patterns and travel behaviour of those who use or patronize the facility. Additionally, special generator survey data can be used to location-specific sub-models within a regional travel demand modelling framework. [**2017 Core Satellite, 4.3**]

2.2.2.1.9 Stated Preference Surveys

Description: The stated preference (SP) survey is part of the "stated response" family of survey data. The purpose of an SP survey is to understand the factors that lead a respondent to choose one of several hypothetical alternatives. This type of survey is best administered using an instrument that can incorporate visual elements so that the characteristics of different alternatives can be presented. A stated preference question may ask a respondent to rank, rate, or choose alternatives. (Correia & Bradley, 2010)

Frequency and Prominence in Canada: The utilization of stated preference data is uncommon and are usually obtained through third-party surveys or surveys that they have commissioned. It appears that there is a desire to use SP data if they were available. SP surveys are often conducted as one-offs, or in an irregular fashion.

Data Collected: In order to gain insights into the factors that affect the preferences of respondents, respondents are often asked to either rate or rank different alternatives or to select their preferred alternative from a choice set (Correia & Bradley, 2010). It has been recommended that each attribute take three values (or "levels") to allow for the detection of non-linear relationships (Correia & Bradley, 2010). SP surveys also tend to collect socioeconomic information in order to facilitate econometric modelling (Correia & Bradley, 2010).

Use Cases: SP data are typically used to gain insights into the perceptions and unobserved factors that influence the preferences of a respondent, based on their selection of an alternative of a hypothetical choice set [**2017 Core Satellite, 4.2**]. SP surveys can also be used to study preferences as they relate to the introduction of a state-of-the-art alternative, i.e. one that is not analogous to an existing alternative (Correia & Bradley, 2010).

2.2.2.1.10 Attitudinal Surveys

Description: Attitudinal data are often collected in an attempt to gain insights into the perceptions and unobserved factors that can affect the decision-making process. Responses to attitudinal questions provide valuable insights into factors such as "attitudinal behavior, family, and social influences; historical context; and the perception of safety and facility quality" (Edwards, et al., 2012).

Frequency and Prominence in Canada: The utilization of attitudinal data appears to be relatively prevalent among Canadian agencies. Many of the agencies that use this type of data obtain it through third-party surveys or through surveys that they have commissioned. Attitudinal surveys are conducted either as a one-off or on an irregular basis.

Data Collected: In addition to socioeconomic data, respondents are often asked to identify the extent to which their behaviour is influenced by various factors. Respondents may be asked to identify factors that encourage them to or deter them from engaging them in an activity or choosing a particular alternative (e.g. mode, route, etc.). Alternatively, respondents may be asked to identify the extent to which a given factor influences their behaviour, often using a Likert scale to do so.

Use Cases: In the context of transportation, attitudinal surveys are typically applied to the study of non-auto modes, such as public transit and cycling. When information is collected using a Likert scale (or another bipolar adjective scale), attitudinal data are often used for factor analysis, model development, and market segmentation (Jin, et al., 2018). Factor analysis aims to identify the set of unobservable latent factors from which all responses to attitudinal questions stem (Cunha-e-Sa, et al., 2012). Market segmentation aims to divide a relatively heterogonous population into several relatively homogenous sub-groups (Li, et al., 2013).

2.2.2.2 OTHER TYPES OF DATA COLLECTED THROUGH SURVEYS:

In addition to data collected through travel surveys (both household and non-household), there are a number of other datasets that are useful when working with transportation data. In this section, five categories of datasets are discussed: the Canadian Census and other StatCan datasets, provincial datasets, municipal datasets, data collected or maintained by professional associations, commercial (private) datasets, and open-source datasets. A brief overview and description of each dataset are provided; for more information see [**TAC P2, 2.0 and Appendix**].

2.2.2.2.1 Canadian Census and other StatCan Datasets

The Canadian Census has been conducted once every five years since 1981. The Census collects a wide range of socioeconomic information that has the potential to support passenger transportation analysis, modelling, and planning applications. Information such as respondent demographics and household characteristics are often used to analyze the representativeness of travel surveys and act as control totals for the expansion of survey data. In addition, datasets such as the CANSIM database and the Labour

Force Survey also contain useful road transportation and employment information, respectively. For more information, see [**TAC P2, 2.2**].

2.2.2.2.2 Provincial and Municipal Datasets

The extensive amount of information collected by municipal and provincial governments are incredibly valuable for urban transportation planning applications. The information contained in municipal datasets includes land use data, transit information, cordon counts, GIS data, and building footprints. Provincial datasets often include land use data, GIS data, motor vehicle registration data, and population and employment forecasts. Using these datasets can be challenging, because they tend to be stored in a format that is not readily accessible, and because historical data tend not to be kept. For more information, see [**TAC P2, 2.3**].

2.2.2.2.3 Data Collected or Maintained by Professional Transportation Associations

Occasionally, professional transportation associations, such as the Transportation Association of Canada (TAC) and the Canadian Urban Transit Association (CUTA) will collect information on travel characteristics, system characteristics, and travel patterns. CUTA collects data through a survey of Canadian public transportation systems. For more information, see [**TAC P2, Sec. 2.4**] and [**TAC P2, Appendix**].

2.2.2.2.4 Commercial (Private Sector) Datasets

In addition to datasets that are maintained by public-sector entities, there are a number of private firms that provide commercial datasets that may be useful for transportation analysis, planning, and modelling applications. Examples of commercial datasets include real estate market data, on-route navigation data, and credit/debit card transaction data. The primary issue with using data of this nature stems from the uncertainty regarding their continued availability. Secondary concerns include costs, the completeness of the data, and the representativeness of the data. For more information, see [**TAC P2, 2.5**].

2.2.2.2.5 Open-Source Datasets

Technological advancements, such as increased access to the internet and the expansion of passive data sources have helped create new opportunities for data gathering. An example within the realm of transportation is Open-street map, which offers a variety of layers that continue to be developed by its community of users. In addition to the increase in the data collected by private firms, the implementation of open data initiatives has also been increasing across Canada. Such initiatives allow members of the public to access data collected by public-sector entities and do not place constraints on how the data are to be used. For more information, see [**TAC P2, 2.6**].

2.2.3 Passive Data Sources

In recent years, there has been an explosion in the amount of data that is available through passive means. These passive sources of data have the potential to produce an entirely new stream of data that can be used to supplement and complement the data collected through a household travel survey. As with any source of data, these new sources of data come with their own set of advantages and disadvantages. This section discusses four types of passive data: smart fare cards, Bluetooth, cellular data, and GPS data. A full critique is provided in [**Final, 7.2**] on the place and potential of passive data in understanding travel demand.

The utilization of smart cards to collect fares is quickly becoming a standard practice among transit agencies. Although the primary purpose of these cards is to facilitate the payment of fares, they can also provide valuable information on transit users. Because smart card systems require passengers to tap their fare card on a reader when boarding a transit vehicle, the location and time at which they boarded said vehicle can be logged. Smart card data provides a near-continuous record of transit usage and is a much larger amount of data than would be obtained through a household travel survey. For a more detailed description of smart fare card data, see [**2016 Passive, 2.2**].

The key challenges associated with using smart fare card data are the lack of associated trip and demographic information and the fact that these data only provide insight into the behaviour of transit users. [**2016 Passive, 2.2**] and [**2017 Core Satellite, 5.3**] provide a breakdown of the challenges that are faced when using smart fare card data. Data collected through smart fare cards are often compiled by transit agencies or the managers of the fare card system. Examples of smart fare cards include the PRESTO card in the Greater Golden Horseshoe (GGH), the bip! card in Santiago, Chile, and the Metrocard in New York City [**2016 Passive, 2.1**]. Applications of smart fare card data are described [**2016 Passive, 2.1**] and [**2017 Core Satellite, 5.3**].

The increased number of Bluetooth-equipped devices, such as cellphones has created the opportunity to keep track of the movements of individual persons and vehicles in a passive manner. The main benefit of using Bluetooth sensors to collect data on travel is the fact that each device has a unique identifier, known as the machine access control (MAC) address [**2017 Core Satellite, 5.4**]. The existence of the MAC address and the binary nature of the detection process allows for the collection of fairly accurate data, with very little information being lost to processing [**2016 Passive, 3.2**]. The main challenges experienced when using Bluetooth data are the need for devices to be discoverable and the inability to record point speeds or trajectories. The issues and challenges associated with using Bluetooth data are discussed in [**2016 Passive, 3.2**] and [**2017 Core Satellite, 5.4**]. Applications of Bluetooth data include the collection of the routes taken by fans arriving at and leaving a college football game as well as a study of the time spent by pedestrians in public spaces. Other applications are discussed in [**2016 Passive, 3.1**].

Due to the high rates of cellphone ownership, call detail records (CDR) have also emerged as a potential source of data for transportation planning applications. Call detail records are compiled by cell service providers for billing purposes whenever a customer makes a call, sends a text, or uses cellular data [**2016 Passive, 4.0**]. Providers will also page devices periodically if service has not been used for a certain amount of time in order to ascertain the location of devices. Collecting spatiotemporal information through cellphone records creates the potential to obtain travel information from a larger population than would be obtained through a household travel survey. [**2017 Core Satellite, 5.2**] discusses the advantages and disadvantages of using CDR data. CDR information has been used to derive trip generation information and OD matrices, and for the validation of speeds and travel times. Additional applications are discussed in [**2016 Passive, 4.1**]

Data obtained by GPS devices is the most commonly used source of passive data. The periodic recording of the location of a device at short intervals allows for the collection of highly accurate spatiotemporal data [**2016 Passive, 5.1**]. GPS devices (including smartphones) have the potential to collect travel time and route information that is more detailed and accurate that what would be reported through a travel survey. In addition, GPS devices also have the potential to collect data over the span of multiple days, due to the low associated costs and response burden. The key issue with using GPS devices to collect travel data is the inability to obtain key information, such as trip purpose, traveller demographics, and household characteristics, through passive means. As a result, the participants of these surveys are often required to validate or provide this information. The collection of location information via GPS can also address issues of erroneous reports and trip under-reporting [**2017 Core Satellite, 5.1**]. The advantages and disadvantages of using GPS data are presented in [**2017 Core Satellite, 5.1**]. Anonymized and aggregated GPS data can be obtained from third-parties such as INRIX or Tomtom. Applications of GPS data include the derivation of multi-day travel diaries and the estimation of route and facility choice models.

2.3 Users and Use Cases

Any re-design of a passenger data collection paradigm should consider both those who will ultimately use the data and the purposes for which these data will be used. When it comes to the TTS, there are a variety of stakeholders and users. The agencies that fund the TTS are, of course, both users and stakeholders. Other users of TTS data can be identified based on the requests that the Data Management Group (DMG) at U of T has received from those who have requested access to the aggregated data. As of March 20, 2018, 168 organizations have requested access to TTS data, representing a total of 818 users. Although it is impossible to know the specific purposes for which they used TTS data, these requests can be categorized by affiliation. A total of seven categories of organization are defined: academia (e.g. universities), consultants, news agencies, non-profit organizations, private organizations, public agencies, and other. Figure 2-2 provides a breakdown of the number of requests for access to TTS data by agency category; Figure 2-3 compares the number of users, by organization type.

Roughly three quarters of requests for TTS data are received from consultants (retained from both public and private entities), public agencies, or persons in academia (Figure 2-2). Many of the users of TTS data either work in academia or for consulting firms (Figure 2-3).

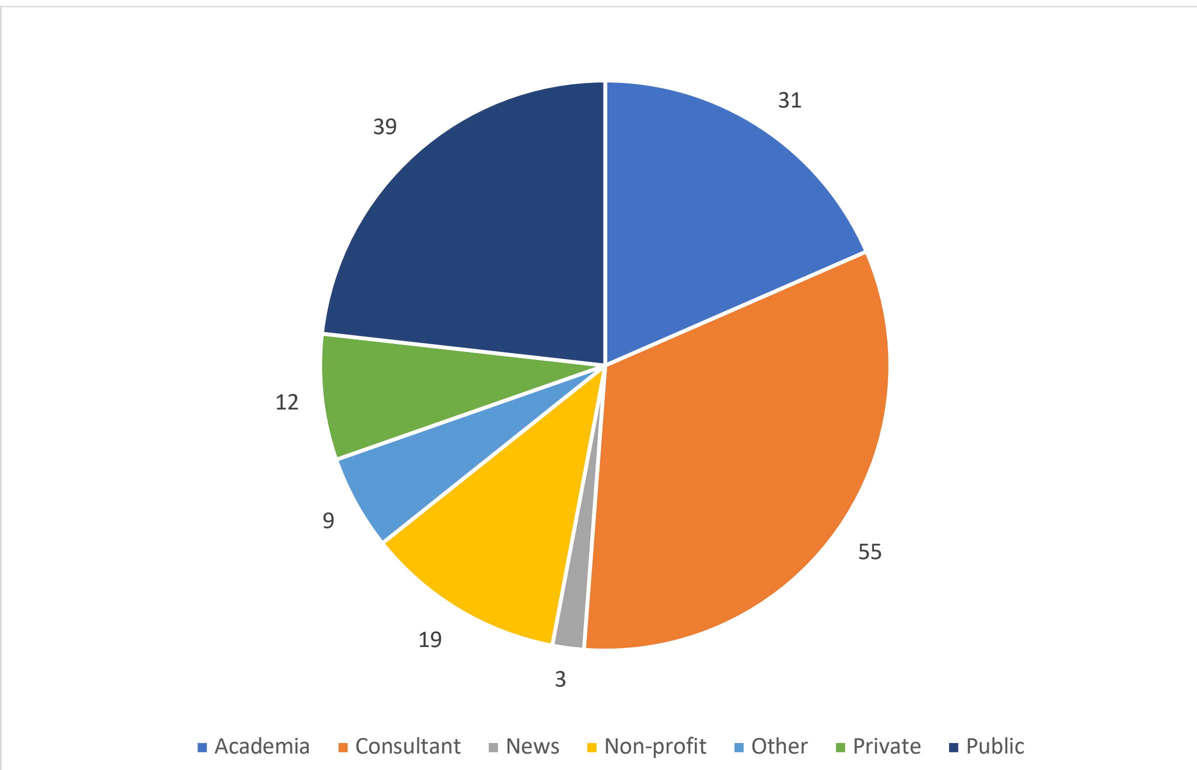

Figure 2-2 Breakdown of requests for TTS data, by organization category

Active survey data, i.e. data obtained through surveys, are often used for planning analysis, constructing travel demand forecasting models, and transit planning applications. Web survey data has been used to understand the utilization of both transportation networks and specific aspects of the transportation network. In practice, web-based surveys have been used to understand the utilization of transit lines and car- and bike-sharing services [**TAC P2, 4.2**]. On the other hand, passive data streams are used for a wide variety of applications. In addition to facilitating planning applications, data obtained from GPS devices has been used to monitor traffic conditions in real time. This information can be used to monitor travel speeds (or travel times) and to support the operational control of highway facilities **[TAC P2, 4.3]**. Data from GPS devices has also been used to study the driving behaviour of participants.

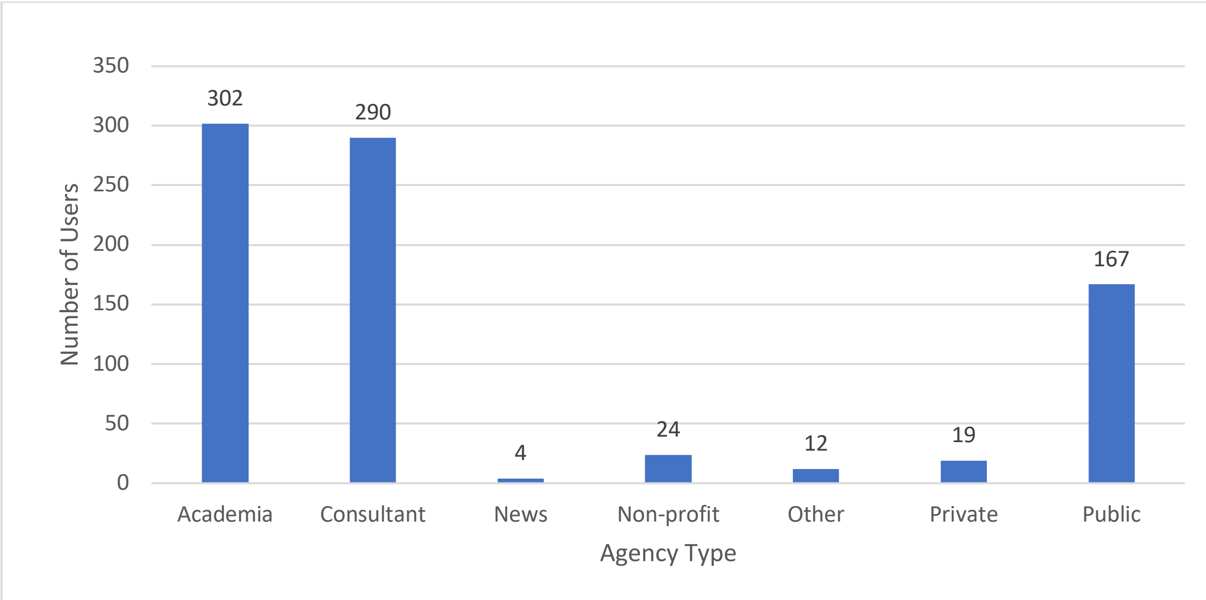

Figure 2-3 Users of TTS data, by organization category

The data obtained through newer streams of passive data has also been applied in practice. Smartcard data are an emerging source of passive data that has proven to be useful in transit applications. Although smartcards are used to facilitate fare collection, the corresponding spatiotemporal information has also been used to analyze the travel patterns of transit users, including the variability of transit use. These data have also been used to create transit origin-destination matrices and forecast travel demand. Data derived from smartcards has also been used to understand the impacts of incidents and special events on transit demand, and to estimate performance indicators **[TAC P2, 4.4]**. Smartcard data has also been used to supplement data collected through household travel surveys.

Data that is collected for billing purposes by vehicle-sharing services (such as car- and bike-sharing) have also been found to be useful in transportation planning applications. The inclusion of GPS devices on cars and bikes allow for the origin and destination of trips to be recorded, in addition to the time and date of usage. This information can facilitate the development of indicators that characterize system supply and demand and have the potential to create travel patterns for analysis **[TAC P2, 4.3]**.

Generally speaking, passive data has been used to study travel behaviour, estimate performance indicators, and have been used as input to travel demand models **[TAC P2, 4.4]**. Table 4.3 in **[TAC P6, 4.3]** classifies sources of transportation data based on whether its applications relate to the behaviour or the characteristics of the system. Active, passive, and hybrid data collection methods tend to be applied to understand the behaviour of the system. Conversely, administrative datasets are typically used to derive the characteristics of the system.

2.4 The future of the TTS

One of the first steps in the design of a passenger travel data collection paradigm for the modern era is to understand the data that are collected through the existing paradigm. In the case of the Greater Golden Horseshoe (GGH) region, data are collected through the existing travel data collection paradigm, i.e. the TTS. The information collected through the most recent iteration of the TTS, conducted in 2016, is shown in Table 2-1.

Table 2-1 Summary of information collected by the 2016 TTS, by attribute

Attribute	Information
Household	• Home location • Dwelling type • Number of household members • Number of household vehicles • Number of driver's licence holders • Number of full-time workers • Number of part-time workers • Number of employed persons • Number of students • Number of household trips • Household income
Person	• Age • Sex • Driver's licence ownership • Transit pass ownership • Employment status • Occupation type • Student status & school code • Availability of free parking at work • Number of trips made by person • Number of transit trips made by person
Trip	• Start time • Primary mode • Trip purpose • Trip origin purpose • Trip destination purpose • Trip origin and destination location • Trip length • Number of people in carpool (if applicable) • Use of highway 407
Transit	• Access mode • Access location • Distance from trip origin to access stop • Egress mode • Egress location • Distance from egress stop to destination • Route(s) used • Subway boarding and alighting stations (if applicable) • GO transit boarding and alighting station (if applicable)

The TTS has been a consistent source of high-quality and standardized travel information for most of its existence, but the emergence new sources of data and the evolution of data needs necessitates an evaluation of the current survey methodology. The over-arching goal of the TTS 2.0 project is to design a modern, comprehensive data collection program that is capable of addressing both the current and emerging data collection needs of the GGH. While this research and development program has primarily focused on studying existing and newer approaches to collecting travel data, this project is also an opportunity to examine each and every aspect of the current TTS. This includes the overall survey framework, the sample frame(s) used, sample size requirements, and the selection of survey modes. As this chapter has shown, passenger travel data come from a variety of sources. This means that in order for a data collection program to be capable of accommodating both existing and emerging data needs, it must be flexible enough to incorporate different sources of data.

3 THE CORE-SATELLITE DATA COLLECTION FRAMEWORK

To date, travel demand data in the Greater Golden Horseshoe Area (GGHA) has been primarily collected via the TTS, which has allowed for a standardized method of collecting key travel demand information across the region. Other regions around the world have similarly relied on regional household travel surveys (HTS) to varying degrees. There is, however, no systemic methodology for handling other types of travel data. This has become problematic with the growing need for more expansive data as travel demand models become more detailed and complicated, particularly in the case of modes other than passenger car or transit [**Final, 2.0**].

This need for expanded data has been counterbalanced with the burden that is placed on respondents. As a result, there is a limit on the number and complexity of questions that can be asked during a large-scale household travel survey, as well as the number of follow-up surveys that can be conducted on the same population. This is of particular concern in an era characterized by declining enthusiasm for surveys and increasing concerns about privacy that have led to decreased response rates and often biased representation [**Final, 4.2**]. This bias has been most noticeable amongst young adults, even in the most recent 2016 iteration of the TTS [**2017 Multiple Frames, 7.0**].

Given these issues, acquiring the needed data has led to additional survey efforts or interest in the use of emerging data sources outside of HTS that produce data that are difficult to fuse. These efforts are performed by a variety of actors (government, industry, and academia) on varying populations, and take many forms. This necessitates a new form of collection paradigm that goes beyond the traditional household travel survey that directly acknowledges the continued trend towards acquiring travel demand data from a variety of sources.

3.1 Basic overview of the core-satellite paradigm

The core-satellite survey framework was originally devised by Goulias et al (2011) and later expanded in the preceding 2012 TAC report. It is an approach for collecting travel data that aims to tackle the specific issue of acquiring demand data from various sources and at varying depths. Its primary goal is collecting the data for highly detailed urban simulation models, therefore requiring data beyond a traditional household travel survey. The original diagram of the core-satellite framework is presented in Figure 3-1.

The framework can be considered to be comprised of 2 original components, the core survey and satellite surveys.

Core surveys are large-sample surveys that collects key demographic and travel behaviour information about respondents. These data are specified by regional authorities as those essential for policy/planning needs. Attributes of respondents are collected to allow for common variables that could be used to link data with those from satellite surveys that are undertaken on a sub-sample of those who responded to this survey. They are performed using a large, statistically significant sample size, allowing results to be expanded to the entire population. These surveys are stable over time, usually collecting the same data each iteration (e.g. trip rates, mode split, general travel demand distribution) with minimal changes in between to maximize comparability. They are conducted frequently or even continuously and are kept short to minimize burden and costs.

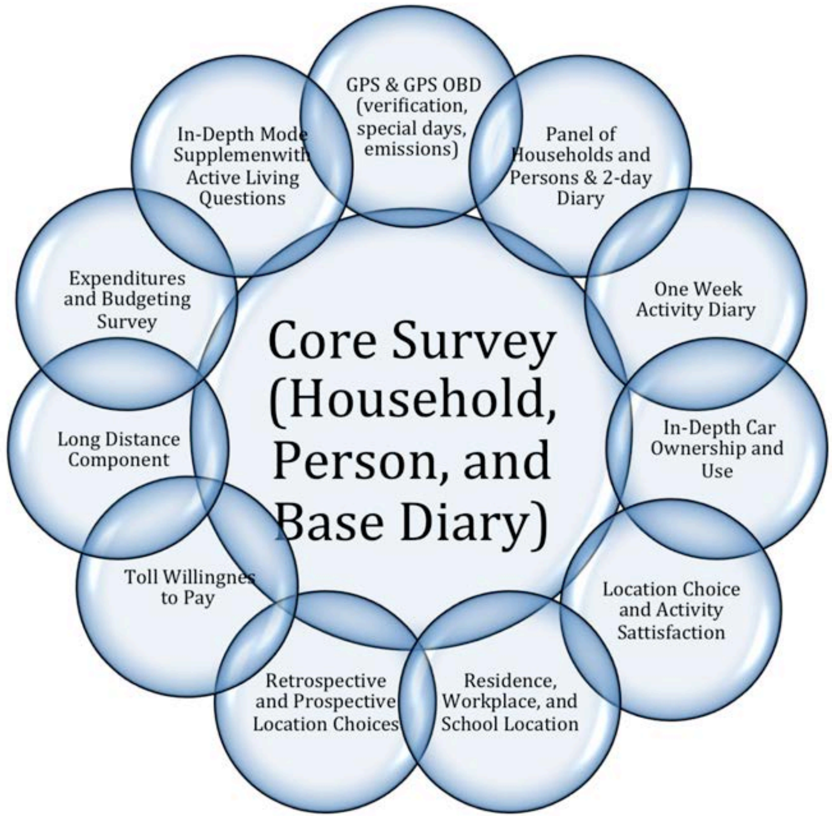

Figure 3-1 Core-Satellite Multi-Instrument Survey Design (Goulias, 2011)

Satellite surveys are smaller and more focussed with the goal of collecting detailed information on specific aspects or populations. These surveys address information that are not collected in the core survey; however, they need some method to statistically link these data to those collected by the core. Satellite surveys can be one-off or recurrent. The data from the smaller satellite surveys are used to augment the core survey, in order to obtain more information on specific subpopulations or specific travel [**2015 Landline, 6.1**].

Satellites can take a variety of forms. Extra questions can be asked of a subset of the respondents of the core survey at its conclusion. Alternatively, follow-up surveys can be later conducted on this subset. Separate surveys can also be done by focussing on specialty populations (a type of stratified sampling). It also allows for passive sources that have clear connective features to allow linking with the core data set.

This category of survey is categorized as such to allow for flexibility to deal with 'hot-button issues' in a more cost-effective manner than attempting to include additional questions in the core survey. While the satellites need not be conducted through the same methods used by the core and could involve different respondent samples, the resulting data must be 'linkable' to the core data set. Goulias proposed a set of possible satellites, as shown in Figure 3-1, that aimed to provide a complete set of data for activity-based travel demand modelling.

The third component was added to the framework in the preceding TAC report [**TAC P6, 7.2**], namely **complementary surveys or datasets**. These were put forth for completeness, accounting for all other data collected by agencies that could potentially be used to understand travel or act as verification/validation data but most likely could not be directly linkable to the core-satellite data.

The rationale behind this approach is based on a few considerations. First, multi-instrument surveys are needed to capture different elements being studied; this is because of the complexity travel and respondent behaviour a single survey may not be able to capture. Second, the approach tackles the need to reduce non-response by reducing and redistributing response burden; response burden tends to adversely affect response rates and data quality [**2017 Core Satellite, 2.1**]. Finally, the framework allows for harnessing of data from surveys and data sources outside of the traditional HTS, warehoused or accessible at a common point.

An expanded core-satellite paradigm The Goulias model and its expanded version in the preceding TAC report acted as the starting point for the data collection framework devised through TTS 2.0. This chapter presents a modified version of the core-satellite framework that has been expanded based on shortcomings of the original framework realized during the course of the project. It is presented after a discussion on gaps found in the Goulias framework. This is followed with details on the various surveys and collection methods and sources that make up the framework, with concrete examples provided, and a framework of how each data collection should be performed. Overall, this chapter acts as a roadmap to the remainder of the final report, where the specific design and execution details are presented.

3.2 Proposed Data Collection Framework

3.2.1 Drawbacks of the Goulias core-satellite model

The initial Goulias core-satellite method assumes a core survey that is representative and complete. Satellites here act not to make up for representativeness issues in the core, but to augment the data that were collected by it to feed more data-intensive travel demand models. This is a strong assumption that unfortunately has become progressively less true over recent years. It has become apparent that even a multi-frame multi-mode household-based core cannot provide a representative and complete sample. Therefore, an expansion of the framework is needed to include a survey category that could address some of the representativeness gaps and provide specific instructions for their undertaking.

Next, the initial framework provides no distinction between different types of satellites. Satellites are instead categorized under a single term, with no distinction made for key differentiators such as purpose, time of conduct and population. An operational framework would benefit from further granularity to allow for specific prescription of methods based on the type, particularly with respect to how to deal with the resultant data. It also does not address specific frames and modes or provide guidance on how to combine dataset produced by the different surveys conducted. This is critical to avoid a situation of survey data dumped into a common store, but without any meaningful way of linking these data; this is particularly important for modelling and analysis purposes.

3.2.2 Purpose and goals of a new framework structure

The main goals of this new structure are to expand on the initial Goulias model to accomplish a few tasks:

- More clearly delineate between surveys with specific purposes
- Address the need for surveys that are meant to fill gaps found in traditional core surveys
- Define final destinations of data and where data fusion needs to be applied
- Incorporate the existence of passive data sets and provide guidance for their use

This system was designed with a specific purpose of serving future TTS (details on motivation for the use of a core-satellite structure can be found in [**2017 Core Satellite, 3.4**]). A core-satellite structure would allow for the TTS to remain as the core survey, collecting primary information useful to all stakeholders in the GGHA. Municipalities and agencies would then be able to focus on their own data collection needs by conducting satellite surveys; their only concern would be to ensure that they collect data that would facilitate fusion with the TTS core data. Satellite surveys could be used to develop sub-models for particular subpopulations or to collect additional information. Standardized methodologies would allow for data to be compared and fused with the TTS core survey based on the application.

3.2.3 Overview of the terminology of the expanded core-satellite framework

A conceptual diagram of the expanded core-satellite collection framework is presented in Figure 3-2.

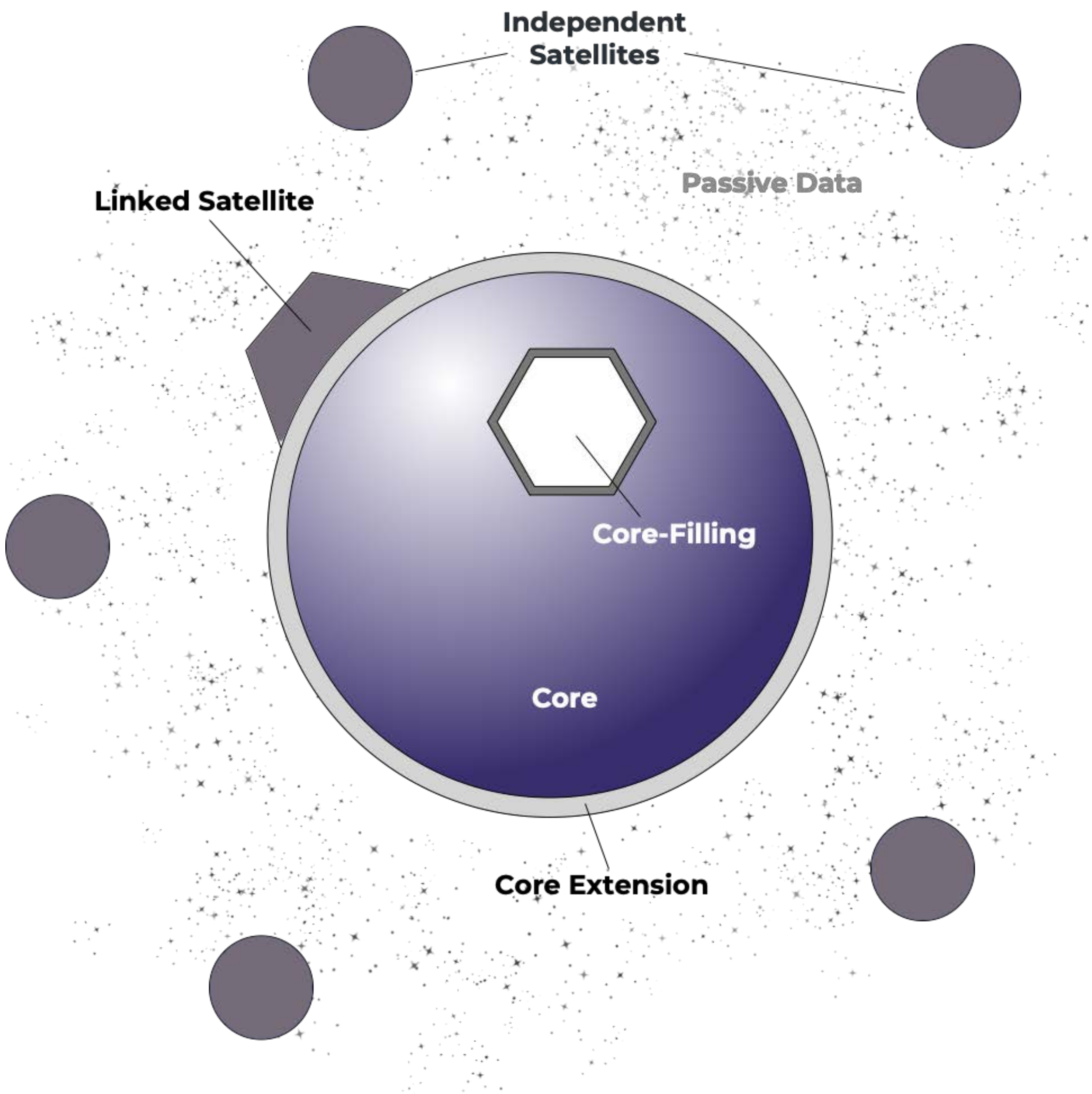

Figure 3-2 TTS 2.0 Expanded Core-Satellite Framework

The survey types in this expanded paradigm/framework still follow the same general division of core versus satellite surveys. These categories, however, were found to be too broad, and so are sub-divided into survey types with specific characteristics and goals. The core surveys encompass the traditional core survey (generally an HTS), core-extension surveys, and core-filling surveys. The satellite surveys are distinguished based on their purposes, whether they aim to address issues in the core or provide a more detailed understanding of travel behaviour, and how their resulting data could be fused or linked with the core data. Satellite surveys are classified into two types: data-fusion-by-design, and independent. Data emerging from these satellites can be integrated with the core data using appropriate context specific data fusion techniques. Finally, there might be other non-survey information which are useful for travel behavior purposes. These comprise the passive data component of the proposed core-satellite paradigm.

Core Survey The core is a large-scale survey that aims to obtain "core" and general information about the population. Traditionally, a regional household travel survey acts as the core survey; however, this may change in the future with improvements in smartphone technology, and evolution of travel survey apps. It is expected that this survey will for the foreseeable future require multiple sample frames and multiple modes of collection, but remain a critical source of travel demand data even with the rise of large-scale passive sources. Additional detail about conducted a core survey is available in Section 3.3 [**Final, 3.3**]

Core Extension Survey Core extension surveys involves the collection of data about certain aspects of travel behavior which do not necessarily require a 5% sampling rate to be statistically significant. The goal of a core extension survey is to help to reduce or spread around response burden while increasing the amount of information collected from the entire population. They ask additional questions to random subsamples of the respondent pool and are conducted at the same time as the core survey, normally at their conclusion. More information about this type of survey is found in 3.4 [**Final, 3.4**]

Core-Filling Survey Core-filling surveys aim to address demographic or geographic gaps, or under-representation present in the core data set. With core surveys utilizing household-base frames, core-filling surveys instead use non-household-based frames selected based on their over-representation on key demographics that are under-represented in the household frames. Two specific core-filling surveys were investigated in the course of the TTS 2.0 project, post-secondary student surveys and employer-based household recruitment surveys (inverted sampling). Further detail can be found in 3.5 [**Final, 3.5**]

Linked Satellite Linked satellites are follow-up surveys conducted after the core that collect additional data about certain sub-populations. As a key trait, linked satellites sample from the already surveyed respondents. This follow-up method provides an explicitly link between the satellite and the core data set to allow datasets to be directly joined. A data expansion or fusion procedure may follow to produce population metrics or a fused data-set. See Section 3.6 for more information [**Final, 3.6**]

Independent Satellite The final satellite category involves surveys that collect data beyond the core for certain subpopulations but do not have an explicit link to the core dataset. The samples of this survey type are taken from a different sample frame from the core surveys, and therefore may or may not have been interviewed for these core surveys.

Passive Data Passive data are those collected often without the knowledge of those being observed, and usually without a specific travel demand measurement intent. These data are often available only in aggregate form but are collected at much larger sample rates than a survey method, while often being collected continuously throughout the year. Generally, as a result of privacy concerns or laws, data collected in this fashion will be missing individual identifiers allowing for demographic analysis or linkage. As a result, appropriate fusion techniques are a pre-requisite for using these datasets. Passive data are dealt with in Section 7 [**Final, 7**].

3.1.1 Determining the type of survey to conduct

With the number of surveys in this expanded framework, choosing the correct survey type for a given purpose and population may be a little overwhelming. Figure 3-3 provides a flowchart to assist in understanding the different surveys of the framework and to determine which survey type would best fit a given situation. Details on execution of all types are contained in the subsequent sections.

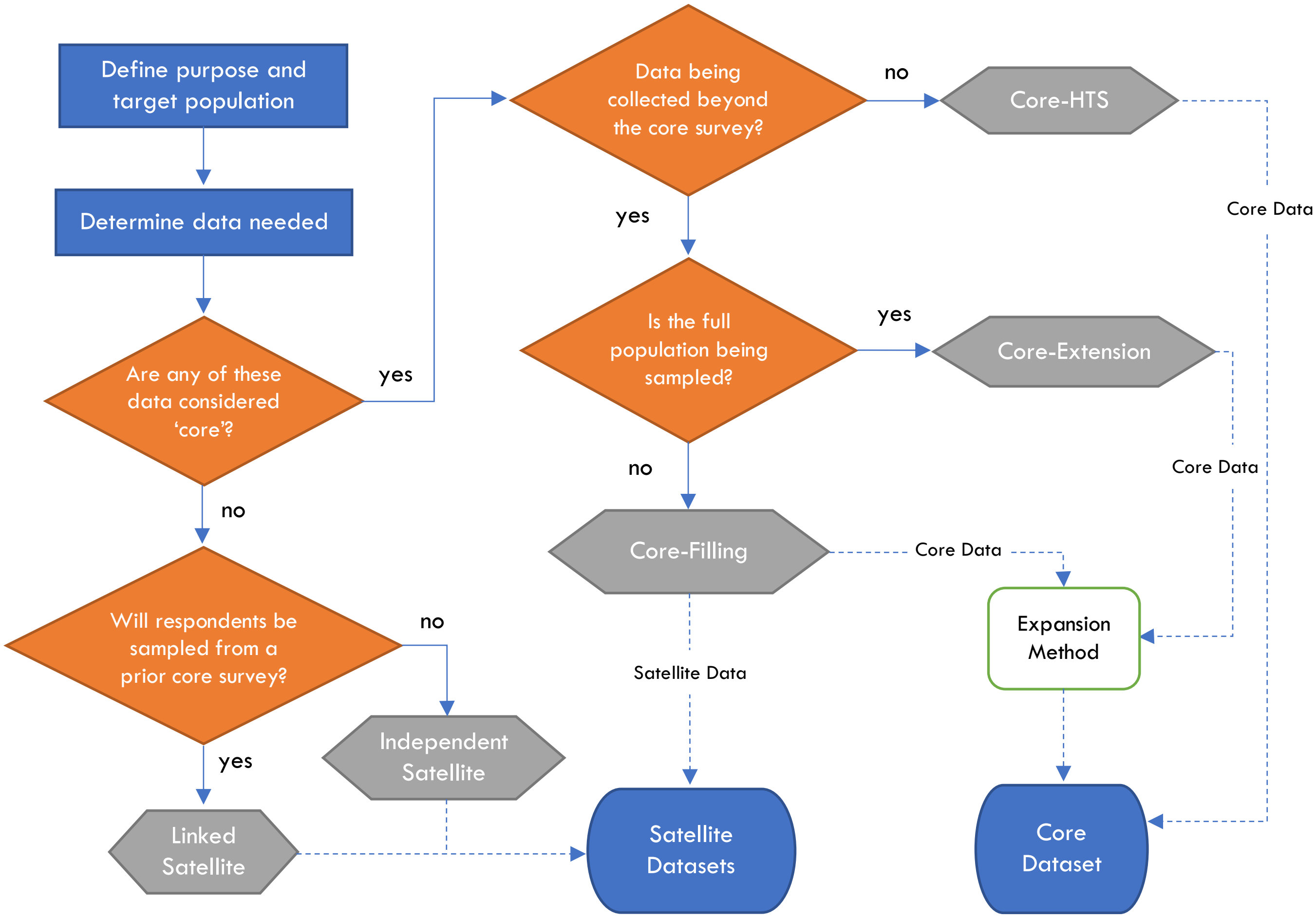

Figure 3-3 Core-Satellite Survey Choice and Destination Dataset Flowchart

3.3 Core Surveys

Core surveys are large-sample surveys that collect primary information that are reflective of the key behaviours that stakeholders wish to capture of the entire population and are critical for policy and planning needs. In the original Goulias framework, this core survey aimed to collect the base information needed for an activity-based travel model, namely key household, person and trip diary data **[Final, 2.2]**. This core data is defined by a set of questions that are asked in the core surveys; this set will vary based on stakeholders and their needs **[Final, 2.3]**. Core questions are limited by length of the survey and complexity of the questions in order to balance response burden and data needs. The recommended set of core questions for the 2021 TTS are provided in Chapter 9 **[Final, 9.2]**.

Within the expanded framework, the two key core surveys are the traditional core survey (an HTS) and core-extension surveys. They are conducted using multiple frames and collection modes, aiming to obtain "core" information about the population in general at statistically relevant sampling rates. The frames that are used in core surveys are all focussed on targeting households (address-based, landline, cell-phone), each with strengths and weaknesses (further detail in Chapter 4). A multiple frame approach is meant to ensure better representation and response rate to combat issues found in individual frames. Given recent trends and results from field tests in the course of the TTS 2.0 project, it is expected that traditional core surveys (core and core-extension in this framework) will still under-represent certain subpopulations.

Representativeness, however, is critical to have data on all population segments to properly reflect travel behaviour and cannot be replaced by data expansion methods that fit to census demographics [**Final, 7.2**]. A third survey type, the core-filling survey, is therefore required to act as a supplement to address these gaps. **[TAC P7, 7.1][2017 Core Satellite, 2.2]**

3.3.1 The Main Core Survey

The main core survey is the foundation of the core-satellite framework, and for travel data collection would generally be a regional household-travel survey (for e.g. the current TTS). It collects the minimum data of the entire population needed to capture the general travel behaviour of the population. This includes some key information relevant for the core-satellite collection structure and to satisfy general travel demand modelling and planning needs:

- Demographic information and any other required data for expansion and for linking to data from satellite surveys, either explicitly or implicitly.
- Permission to perform follow-up surveying with a direct method of contact (phone, email) for later satellite surveys
- Trip diary to gather data on the general travel patterns of the population with a key emphasis on commute travel (AM/PM peak) for city infrastructure planning purposes

Not all data needs to be collected at a 5% sampling rate to be statistically significant [**Final, 4.3**]. For those that do not need a 5% sampling rate, a Core Extension survey method should be considered. This would help to reduce the response burden to in-turn help increase completion rates.

Methodology As with all surveys, the method behind conducting a core survey follows some standard steps. These were presented by Cochran in 1977 and still apply generally [**TAC P2, 2.2**].

1. Establish clear statement of survey objectives
2. Define the population to be sampled and the target groups to be focused on
3. Identify the specific data that are relevant for the purpose of the survey
4. Specify the degree of precision required from the survey results
5. Determine the methods to be used in obtaining the survey results
6. Divide the population into sampling units and list the units from which the sample will be drawn
7. Select the sampling procedure and sample size
8. Pretest the survey and field methods to ensure that the procedures are workable, and the survey is understandable
9. Establish a good supervisory structure for managing the survey[2]
10. Determine the procedures for analyzing and summarizing the data
11. Store the data and analysis results for future reference[2]

While these steps are universal, care must be taken in a few of these steps in order for the core survey method to minimize issues found in the course of the TTS 2.0 project, and to fit within the larger core-satellite paradigm. These modifications and considerations are indicated for the core survey with links to relevant sections in this report for further information.

[2] out of scope

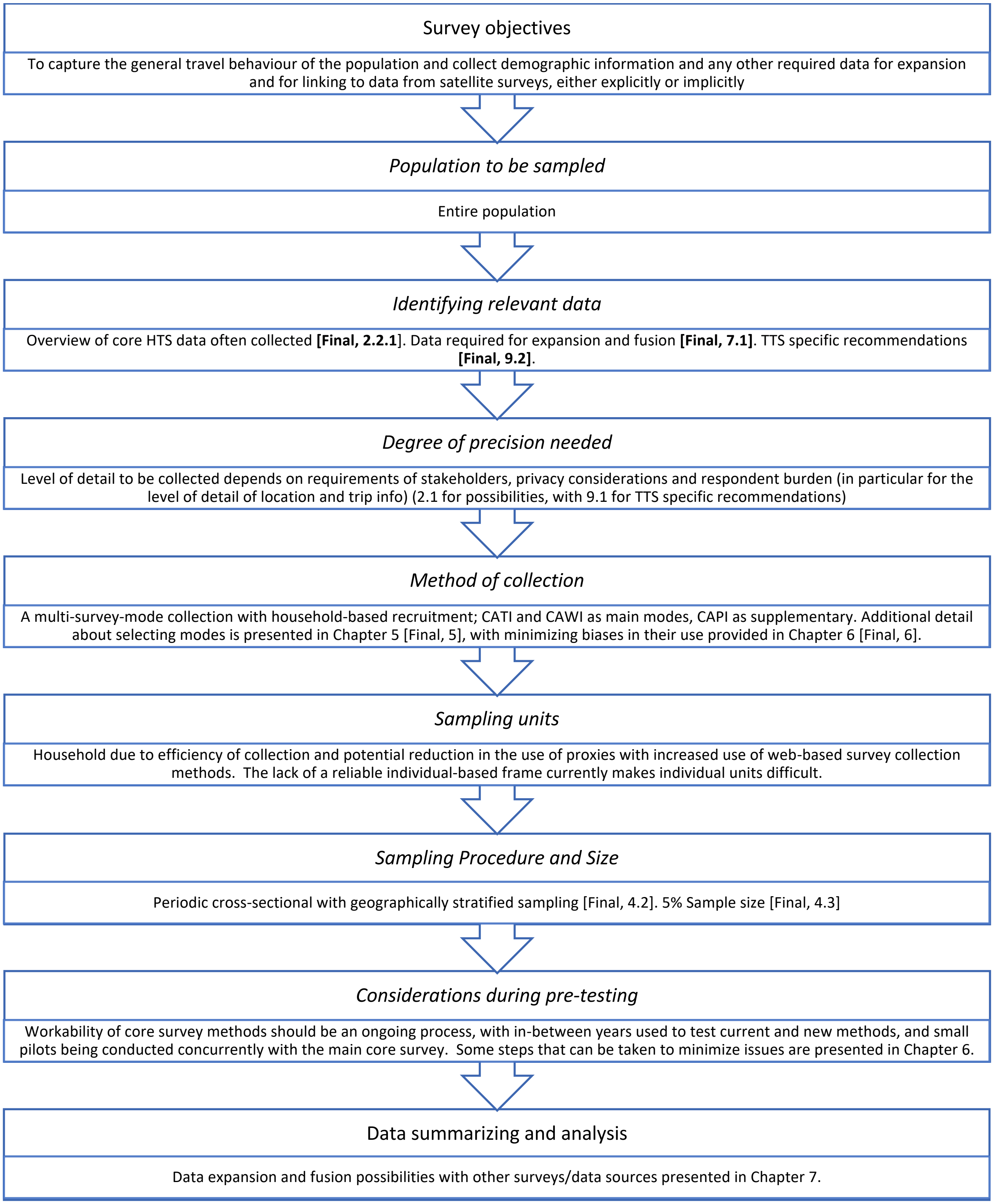

Figure 3-4 Core-Survey Steps

3.3.2 Core-Extension Surveys

Core extension surveys allow for additional core questions to be asked of the core sample without increasing the survey length and response burden on the entire survey population. Extension surveys should be appended as additional questions to the core survey for a randomly sampled subset of the core population. Core-extension surveys can take a variety of forms, for example, a long-distance survey or a smartphone GPS survey.

As a result of being attached to the end of the core survey, there is little change to Cochran's survey steps described for core surveys. A key difference is the sampling rate, with core extension questions not needing to be asked at a 5% sampling rate to be significant. This allows the collection of additional data without increasing the survey length for all core respondents, or by distributing this burden across respondents. The resulting data can then be directly appended to the respective records of the core data from the core survey.

Use of a core-extension survey requires some careful consideration. Completion rates of the extension surveys need to be monitored to ensure that sufficient samples are collected. One also has to be mindful of the number, size, and complexity of the core extension question set; too large of a set can increase the survey length and burden for certain respondents and reduce completion rates. Alternatively, some questions should be considered for a satellite survey [**Final, 3.3**] or asked in a separate follow-up survey; the latter, however, is not recommended as field tests have shown that they reduce response rates [**2017 Web Field, 4.2.4**]

3.3.3 Core-filling

In an ideal situation, core surveys would be representative, broadly covering all demographics and sub populations; however, as illustrated in the studies conducted in this project, shifting communication technologies and technological habits, and dropping enthusiasm for responding to surveys has led to strong respondent biases, particularly for younger adults. This has led to problems in the resulting survey data, with mode splits and trip rates becoming less reliable. In such a situation, merely performing normal expansion procedures to match census demographics does not account for the loss of info, and key relational data goes uncollected, particularly important for more in-depth study on the disaggregate survey data.

Sections of this report (4-6) present various considerations and methods that can be used to attempt to reduce these issues; however, even with best efforts, the traditional HTS acting as the core is sufficient on its own moving forward. Core-filling surveys are instead meant to address these gaps in representation by using non-household-based recruitment methods [**Final, 4.1.1.4**] to collect at-minimum the same core data from under-represented groups.

The idea of core-filling surveys is a new concept presented in this report and attempted in the course of the TTS 2.0 project, with no prior direct implementation. There are, however, examples of similar methods, albeit not to directly fill gaps in a core survey. These include the Utah College Diary Survey and the StudentMoveTO survey; the method was also attempted as a field test in the course of this project [**2017 Inverted Field**]. The Utah College Diary Survey, part of the Utah Travel Study, involved surveying students across 8 post-secondary institutions in Utah about their demographics, travel habits and attitudes for off-campus trips; treated as an independent satellite, however, data collected did not mimic the core HTS [**2017 Core Satellite, 2.5**]. The Student Move TO survey similarly surveyed students via email across 4 university campuses in Toronto; conducted as an independent survey, data collected was focussed on better understanding the travel of students, both on and off campus; the method showed the viability of reaching out to students via their institutional email. Finally, the inverted sampling method field test investigated using a similar e-mail-based contact method to recruit respondents via their place of employment. While results were mixed, some positive signs were observed in the willingness of businesses most likely to employ hard-to-reach groups (namely retail) to participate and assist in distribution.

To be part of the integrated core-satellite collection system, core-filling surveys should be conducted either at the same time as the core or around the same time as the core to minimize temporal biases. Alternatively, they could be conducted within a reasonable period but in the same season to address gaps observed in a recently conducted core survey (e.g. the subsequent fall). These types of surveys will generally use cluster sampling or whole population surveying (with all members of the institution or company receiving recruitment emails).

To conduct a core-filling survey, Cochran's 11 steps can again be followed, customized to address the specific purpose of this survey type:

Survey objectives

To capture travel behaviour of a specific cohort of the population under-represented in the core survey.

Population to be sampled

Depends on the gap observed in the core survey; based on trends seen in recent HTS, this will generally be younger adults.

Identifying relevant data

At minimum the same questions as the core. Additional questions can also be asked which are relevant to vector of distribution. To follow-up with respondents, a question is needed to allow for a direct method of contact (phone, email).

Method of collection

Given the email-based recruitment normal with core-filling surveys, a web-based method with phone/web-audio based support is the best approach **[Final, 5.2] [Final, 6.1.3]** In-person interviewing also possible where permitted by the institution or company **[Final, 5.4]**.

Sampling units

Dependent on the population being targeted. For a post-secondary survey, an individual student is the unit; on the other hand, when recruiting via place-of-employment, a household unit would be more appropriate to produce data consistent with the core survey.

Sampling procedure and sample size

Cluster sampling (usually all members of an institution will be emailed) [Final, 4.2]. Sample size dependent on data being collected [Final, 4.3]. Screening method for overlap with core surveys (i.e. screening out data from students who live off-campus with their parents).

Considerations during pre-testing

Additional work is needed to cultivate relationships with distribution vectors ahead of time to minimize costs by maintaining willing partners over subsequent survey cycles.

Data summarizing and analysis

Data should be split into two parts, with core data being joined with the core database, with extra data stored within the satellite databases, while maintaining linking identifiers. Specialized weighting factors will be required during the expansion process.

Figure 3-5 Core-Filling Survey Steps

3.4 Satellite Surveys

There may be a need to collect data beyond the core to better understand the travel behaviour of a certain cohorts or subpopulations in greater detail. Goulias' core-satellite framework recommends that satellite surveys should be conducted to supplement the core. In this expanded framework, satellites maintain the same purpose but are divided into two main categories based on their ability to easily link data with the core data:

- Linked satellite
- Independent satellite

The following sections provide detailed descriptions of each type of satellite survey, with a case study example of how to conduct one to be consistent with the core-satellite framework. Chapter 9 provides specific recommendations for satellites that should be considered as part of the Core-Satellite TTS 2021 Collection Framework. They can be conducted either as part of the TTS or 'officially supported' to allow agencies and consultants to independently perform them for later processing (including possible data fusion).

3.4.1 Linked satellites

Some additional data beyond the core may be of interest for certain populations. Examples include active mode surveys to collect data on often-missed walk or bicycle trips and GPS surveys for detailed route collection for specific modes. Linked satellites are differentiated from core-extension surveys by being focussed on a specific population, with respondents re-sampled from the core survey respondents. Like the core-extension methods, questions can either be appended to the core survey or a separate follow-up survey can be conducted; if the former, the total length of the survey needs to be considered to avoid excessive survey length and respondent burden.

Since the core data of the respondents are already collected in the core surveys, linking data are already collected to directly match data collected in linked satellites. Data can be appended directly to respondent record in the core data set as additional fields or kept in a separate database with a common unique identifier to allow linkage via database queries.

Survey objectives

To capture more detailed or different travel behaviour of a specific cohort of the population than what was collected in the core.

Population to be sampled

Can be any subpopulation sample of the core respondents, but not randomly sampling from all respondents.

Identifying relevant data

By subsampling from the core data, need only to focus on the additional data wishing to be collected, with link information maintained implicitly. Examples of potential data in **[Final, 2.2.2]**

Method of collection

Depends on the direct contact information available from the core survey and on the data being collected. Ideally, methods employed should mimic those used by the core surveys to maximize data harmonization. **[Final, 5]** can assist in choosing appropriate method.

Sampling units

Dependent on the population being targeted. Care has to be taken in achieving a representative sample if the individual rather than household is chosen as the sampling unit. Otherwise, an independent satellite might be more appropriate.

Sampling procedure and sample size

Random sample of a specific cohort of the core sample. May be stratified geographically based on intended use of the data. **[Final, 4.1-4.3]** for details.

Considerations during pre-testing

Depending on the time period of survey conduct, seasonality issues may need to be considered. Biases in recruitment, questionnaire design, and mode need special consideration, with incentives being a possibility based on burden or target population. **[Final 4.4, 6]** for details.

Data summarizing and analysis

Data should be stored initially within the satellite databases while maintaining linking identifiers. Expansion or fusion methods will be required for extrapolation to the population **[Final, 7]**.

Figure 3-6 Linked Satellite Survey Steps

3.4.2 Independent Satellites

Surveys not collected as a follow-up survey to the core cannot be directly linked to the core dataset. However, these surveys may be important to understand the travel behaviour of certain populations. Examples include HOV usage surveys and intercept surveys, both for transit and active mode. Data fusion methods [**Final, 7**] may be an avenue to link these independent satellites to the core dataset, through either explicit or implicit matching techniques. A framework for this is provided in Chapter 7; however, specific methods are currently context specific. At minimum, performing any fusion method requires independent satellites to collect key variables to allow for fusion.

Survey objectives

To capture more detailed or different travel behaviour of a specific cohort of the population than what was collected in the core.

Population to be sampled

Can be any subpopulation of the full population frame(s).

Identifying relevant data

Relevant data to be collected will be context specific; however, unlike with linked surveys, relevant core linkage variables need to be collected. Generally, this will be demographic data, and possibly mode choice data, to allow for matching and expansion.

Method of collection

Depends on the way the target population is recruited and data being collected. Ideally, methods employed should mimic those used by the core surveys to maximize data harmonization. **[Final, 5]** can assist in choosing appropriate method.

Sampling units

The appropriate sampling unit is dependent on the data being collected and population being targeted, but most likely should be the individual rather than the household (where another survey type would be more appropriate).

Sampling procedure and sample size

Sampling method will vary based on recruitment method employed and intended use of the collected data. Could involve random, cluster or geographically stratified sampling. **[Final, 4.1-4.3]** for details.

Considerations during pre-testing

Depending on the time period of survey conduct, seasonality issues may need to be considered. Biases in recruitment, questionnaire design, and mode need special consideration, with incentives being a possibility based on burden or target population. **[Final 4.4, 6]** for details.

Data summarizing and analysis

Data should be stored initially within the satellite databases while maintaining linking identifiers. Expansion or fusion methods will be required for extrapolation to the population **[Final, 7]**.

Figure 3-7 Independent Satellite Survey Steps

3.4.3 Case Study: Conducting an Active Mode Satellite Survey

The increasing prominence of travel by active modes (i.e. walking and cycling) due to the health and environmental benefits of using these modes, particularly cycling, has increased the importance of understanding the demand for these modes. The need for active mode satellites stem from under-reporting of short trips and low mode shares of active modes [**2017 Core-Satellite, 3.3**]; for example, there is typically an underrepresentation of cycling in traditional HTS. There is, however, a lack of standard guidelines [**2017 Core-Satellite, 3.3**].

Active mode surveys can be conducted either as a linked satellite or as an independent satellite, depending on the method of sampling and sample frames used. An assumption is made before their conduct that the core HTS has overcome issues in representativeness where bicycle users are not under-represented. This could involve targeted student surveys or an inverted sampling method via the membership of cycling associations. Given this, the purpose of linked or an independent active mode satellite would be to collect additional detail on active mode trips or promote entry of short trips that may have been omitted during the core survey. A linked survey would perform this as a follow up survey of a subsample of bicycle users of the core sample. One example of how to perform an active mode survey can be found in a related report [**2018 Ottawa**].

3.5 Passive Data

Passive data encompasses all non-survey data collected through means that do not directly question those being observed. While specific details describing passive data can be found in [**2017 Core Satellite, 5**] and [**2016 Passive Data**], in general, passive data can be broken down into two categories:

- Data collected passively for a specific transport purpose (e.g. smart card)
- Data collected about the population or surroundings that incidentally have a transport application (e.g. cellphone tower traces, census information, targeted marketing data)
-

Both types have value within the core-satellite structure; however, those collected for a specific transport purpose will have greater potential of complementing or replacing current survey-based data rather than acting to provide context or aid in expansion or validation of survey data. A full critique is presented in Chapter 7 of the report [**Final, 7.2**]. However, there remains significant research required to fully harness available passive sources.

Applications of passive data in the core-satellite framework can take several forms. These include providing additional context (e.g. weather or level of service on trip diary days), providing a means to update OD matrices in between survey years [**2016 Passive Data, 3**], replacement of correction of trip diaries [**2016 Passive Data, 2**], validation and expansion, and as input data sources for a population synthesis framework [**2016 Passive Data, 2**]. The latter has been a recent area of commercial interest, with some entities providing fully synthesized populations without any survey data; however, relationships between variables may not be maintained leading to problematic analysis when judging reactions under hypothetical planning scenarios.

3.6 Putting the Framework into Practice

The remainder of this report provides the detail on the various aspects of survey design and execution necessary to implement the framework summarized in this chapter. Of particular note is Chapter 8, which presents a software solution, TRAISI, that was developed in the course of the TTS 2.0 project. TRAISI aims to provide a means with which to operationalize the framework while also acting as the long-term survey and data platform for TTS and related surveys.

Overall, however, it must be noted that this project was carried out in the midst of a data revolution. While smartphones have become ubiquitous and large-scale passive data sources have started to become available, there remains significant questions surrounding processing algorithms, data access, privacy and means of data fusion that have limited their investigation into their role in explaining travel demand into the future. As a result, while significant research has been performed in the TTS 2.0 project, this report points to the need to continuously evaluate and update methods as these new sources mature in order to maintain the relevance of the TTS and harness these sources to better understand passenger travel.

4 SAMPLING FRAMES AND METHODS

As surveying all members of a target population in an HTS is rarely feasible, a sample of the population has to be relied upon to understand its underlying characteristics; however, this requires the sample to be unbiased and of sufficient size to allow for statistically valid inferences about the travel behavior of the population. A prerequisite to drawing such a sample is the selection or construction of a sample frame containing a sufficiently complete list of contact information of the population of interest.

In addition, an appropriate sampling procedure is necessary. Generally, the end goal of the survey determines the sampling method to be used. Since the aim of an HTS is to capture the distribution of travel behavior within the population of interest, probability sampling is usually used. As such, the discussions presented in this chapter are mostly limited to this type of sampling. This chapter presents a synthesis of the studies conducted on the sampling procedure within the TTS 2.0 projects. This includes a critique on sample frames and sampling methods, procedures to determine appropriate sample size and best practices on recruitment and incentives.

4.1 Critique of various sample frames

The 2012 TAC Report defines a sampling frame as the operational method of (at least implicitly) enumerating/listing the population from which the survey sample is to be drawn [**TAC PII, 2.2.1**]. As discussed earlier, selection of a proper sample frame is the prerequisite for a successful data collection effort. This section discusses the sample frames under two categories that are characterized by whether the sample frame explicitly lists the survey population: closed frames (containing sufficiently comprehensive list of the target population) and open frames (which do not list the survey population explicitly). The following subsections present critiques of the different sample frames included in each of these categories based on their advantages, disadvantages and current applicability for large-scale HTS like the TTS.

4.1.1 Closed frames

4.1.1.1 LISTED LANDLINE FRAME

The landline frame is comprised of listed landline phone numbers (with addresses) which are used to contact households to conduct CATI surveys, or to recruit them for online surveys. The frame list is acquired from directories of landline phone numbers. In the past, this frame adequately represented the population; as a result, many Canadian surveys used it to draw representative samples [**TAC PII, 2.2.1**]. The TTS, for example, used the telephone directory as its only sample frame until 2011. The registry of landline phone numbers makes for a relatively large sample frame that is quite easy to access and is the least costly of the available household-based closed frames [**TAC PII, 2.2.1**]. Moreover, it tends to produce higher response rates through telephone interviews compared to address-based sampling. In the 2016 TTS, the response rate for the landline frame (i.e. address/phone frame) was high (39.6%), while address-only and phone-only frames' response rates were much lower at 10.5% and 8.6%, respectively [**2017 Multiple Frames, 8**].

However, with time the landline frame is becoming an incomplete frame mainly due to the increasing number of households that do not own a landline. According to Statistics Canada, 27.1% of households in Ontario reported not having a landline in 2014, increasing to 36.6% in 2016. Research has shown that the socioeconomic characteristics and trip pattern of individuals in cellphone-only households are different from those with landlines [**TAC PII, 2.4**]. As such, missing cellphone-only households results in a biased travel behavior representation. Also, landline telephone interviews tend to under-represent households with younger, lower-income residents (18-34 years old) [**TAC PII, 2.4**]. Moreover, CATI household interviews are subject to survey mode bias and proxy bias, details on which can be found later in the report [**Final,**

6.1 and 6.4]. Owing to all of these reasons, the landline frame is becoming less representative of the population with time.

It is anticipated that the representation issue of the landline sample frame will become more acute in the future for several reasons. These include the growing trend of landline-less households, the growing subscription to VoIP services and the implementation of National Do not Call List [**TAC PII, 2.4**]. As such, the use of the landline register as the only sample frame will decrease with time. In fact, the most recent iteration of the TTS in 2016 used the landline frame in conjunction with address-based sampling [**2017 Multiple Frames, 8**]. This trend is likely to continue into the future.

4.1.1.2 ADDRESS-BASED FRAME

The address-based frame list is usually acquired from address registers of postal services. For example, Canada Post maintains the Canada Complete Mailing List which potentially includes all residential and commercial addresses. Although mail surveys are typically conducted with this frame, it can also be used to recruit households for online surveys. The address-based sample frame has gained prominence due to the availability of address registers and their high coverage of households [**2016 Sample Frame, 4**]. In fact, the TTS introduced the use of address-based sampling in 2016; this was part of a shift to the use of multiple sample frames (address & phone (landline), phone-only (RDD, verified cell phone listings), and address-only (ABS)) in order to attempt to improve representation of the population of the survey area.

Advantages: The main advantage of using an address-based frame is its large coverage. The address-based frame is often considered as a potentially complete list. For example, Canada Post claims it has the biggest mailing list in the country. The Canada Complete Mailing List is considered to have all the address of households within Canada [**2016 Sample Frame, 4**]. Thus, it can be a source from which potential representative samples of the population are drawn.

Disadvantages: Address-based frames, however, are faced with the problem of low response rate. Analysis of the 2016 TTS data revealed that the address-only sample frame has a 10.5% response rate which is considerably lower than the address/phone response rate of 39.6% [**2017 Multiple Frame, 8**].

In terms of population representation, although the address-based frame has the potential to provide a representative sample, it faces some issues owing to the survey mode used (mail-back, CATI or web). In general, mail-back surveys tend to over-represent older middle-class females with higher education (above high school diploma) [**2016 Sample Frame, 4.2**], whereas web surveys tend to over-represent younger, wealthier males who possess higher levels of education [**2015 Web, 2.1.1**]. The address-only respondents of the 2016 TTS were more likely to participate in the web survey, while respondents from the other two groups (i.e. address & phone and phone-only) were more likely to participate over the phone [**2017 Multiple Frame, 8**]. Such mode preference induces mode-specific bias in the sample. For example, the median age of address/phone respondents of the 2016 TTS was higher than census median, whereas that of address-only samples was in line with the census [**2017 Multiple Frame, 8**].

Prospects: Based on the above discussions, it is evident that although the address-based frame is potentially complete and representative of the population, the low response rate of mail surveys and survey mode biases continue to threaten its future prospects. To tackle these problems, several techniques can be adopted, such as providing incentives and follow-up mails and inviting respondents from the address-based frame for web surveys. Details on the roles of incentives and follow-up letters in improving response rate can be found in later sections of the report [**Final, 4.4 and 5.3**].

4.1.1.3 CELL PHONE FRAME

In recent times, the cell phone sample frame has gained popularity due to increasing numbers of unlisted landline phones and growing numbers of cell phone/smartphone users. The frame list can be constructed from Random Digit Dialing (RDD), verified cell phone numbers' lists, or cell phone only (CPO) households' lists. In Canada, marketing firms like ASDE Survey Sampler create cell phone samples by generating random numbers from the list of existing dedicated cell phone exchanges [**2015 Smartphone, 6.2**]. Usually, the cell phone frame is used to contact individuals for conducting CATI surveys.

Advantages: The cell phone frame has immense potential in the Canadian context, given that smartphone penetration in Canada has been rising very quickly, from 33% in 2012 to 56% in 2013 to 73% in 2014. Moreover, the proportion of households who report exclusive use of cell phones rose from 13% in 2010 to 21% in 2013. In Ontario, almost 85% of households have at least one active cell phone [**2015 Smartphone, 1**].

This rising cell phone ownership is increasing the need to consider the cell phone frame in large-scale travel surveys. Within the Canadian context, the cell phone frame might be critical for sampling younger population groups who are otherwise missed in landline frames. This is because exclusive cell phone use is more pronounced in younger Canadian households, where all of the members are under 35 years of age. In 2013, 60% of these households reported using a cell phone exclusively, up from 39% in 2010 and 26% in 2008 [**2015 Landline, 2**].

As socioeconomic characteristics and trip pattern of the CPO households are different from households with landlines, the use of the cell phone frame within a multi-frame approach may be necessary to collect a more representative set of data about travel behavior of the overall population. For example, cell phone-only Americans tend to be younger, less affluent, and less likely to be married or own their home. On the other hand, university students in Toronto with a land line are more likely to live in houses, with parents, and to live in suburban areas than students without a land line. They also make fewer trips in total, fewer discretionary trips, more transit and auto trips, and fewer active trips than students without a land line. **[TAC PII, 2.4]**

Disadvantages: Irrespective of the rising need to consider the cell-phone frame to reach CPO households, there are disadvantages to its use. These include low connection and response rates, higher costs, the inability to target specific geographies and potential issues in being able to extrapolate results to the population.

The very low connection rates of RDD is a primary concern. According to ASDE, a connection rate in the range of 50-55% is achieved using this method, but the response rate is significantly lower. Such low connection rates lead to increased survey costs. In the U.S., cell phone samples achieved via RDD can be 2 to 3 times more expensive than RDD of landline samples. This connection rate can be improved by working with pre-screened or 'working' cell phone numbers; however, as the numbers purchased are guaranteed to be working cell-phone numbers, the list is more expensive than RDD. The most expensive option is to purchase the list of CPO households, since further screening needs to be conducted to filter CPO households from the working cell number database. [**2015 Smartphone, 6.2**]

Low response rates when recruiting via cell phone is an additional concern. For example, to account for this growing trend in CPO households, a phone-only (RDD of unlisted landline numbers, verified cell phone listings, white pages listings with no address) sample frame was used in 2016 TTS in addition to address & phone (landline) and address-only sample frames. However, its use was discontinued two weeks after introduction due to a low response rate and the resulting low interviewer morale [**2017 Multiple Frame, 8**].

The ability to generalize results of surveys that use a cell phone frame depends on the construction method of the frame. If the frame list is constructed by RDD, the phone numbers obtained are random; hence, the results of the survey can be projected to the target population. Moreover, the cell number can be linked to a Canadian Census Division, thereby providing a means by which to check the geographical representation of the sample. However, the cell numbers cannot be linked to smaller geographical areas, like a census subdivision (i.e., a municipality), and as a result makes targeted smaller zones (like TTS analysis zones) impossible. Samples drawn from the lists of CPO households are not random. Hence, the results are not probability-based and cannot be projected to the general population.

Prospects: As discussed, low connection and response rates are a primary barrier to the use of cell-phone frames. To overcome this issue, sending pre-notification text messages could be considered [**Final, 4.4.1**]. There are additional concerns with respect to difficulties conducting geographically stratified sampling, important for the TTS context and project results to the general population. Hence, the cell phone frame has more potential as a complement in a multi-frame approach, instead of a standalone frame.

4.1.1.4 COMPANY/INSTITUTIONAL FRAME

As a result of the issues experienced with household-based frames, 'alternative' frames were examined in the course of the TTS 2.0 set of projects. These 'alternative' frames are those which provide access to specific segments of the population, but whose recruitment vector is not household-based. Two types of these frames were selected for further study: post-secondary school email-list and employee email-list frames. Details on these alternative frames can be found in [**2016 Sample Frame, 8**]. In both cases, the institution or company is contacted and recruited to distribute the travel survey to their students or employees, with the possibility of additional questions tailored to the needs of the institution or company.

An educational institution-based frame was field tested in 2015 with StudentMoveTO [**2016 Sampling Frame, 8.1**]. The goal of the survey was to promote and improve mobility for students within the GTHA. The survey collected data from the City of Toronto's four universities (OCAD University, Ryerson University, University of Toronto and York University) with a combined student population of about 184,000. Students were contacted via their institutional email addresses, and the survey received a response rate of 8.3%.

This TTS 2.0 project conducted initial field tests of a similar approach (coined inverted sampling) via private companies and public agencies. The aim of the field test was to conduct a TTS-like household travel survey by recruiting residents via their place of work, i.e. by recruiting businesses to distribute the travel survey to their employees. Details of the survey can be found in the 2017 Inverted Sampling Frame report.

Advantages: Several benefits of using these types of alternative frames were identified in the surveys. First, large institutional or company email-frames, once recruited, provide a method of large-scale respondent recruitment at relatively low cost. To combat generally low response rates via email, these frames rely on the idea that having the backing of an individual's employer or institution would provide added authority in promoting the taking of the survey. Second, as the alternative frames are mostly email address based, the resulting web-based surveying allow for low cost data collection. As such, there have been successful implementations of these types of surveys (Statistics Canada employee surveys, SmartCommute, and StudentMoveTO) in Canada. Third, demographic targeting is possible with these types of frames. For example, the post-secondary frames deal specifically with a known under-represented/hard-to-reach population of students. Similarly, company-based frames can also bias towards specific groups based on known make-ups of certain sectors. The field test conducted on private businesses display some interesting positives. These include:

- High initial interest in participating
- Proportionally high interest from businesses heavy on demographics that are under-represented (retail sector)
- Decent response rate for those businesses that followed through (11%)
- Demographics are disproportionately younger (expected with exclusion of retirees)

Disadvantages: Mixed results have been obtained to date in the use of these types of frames. Although the post-secondary school email list allowed the survey administrators to reach a large body of students, the StudentMoveTO survey had a relatively poor response rate (8.3%). This should be placed in context, given that younger individuals are known to be harder to recruit for surveys. Such a low response rate could have resulted from instrument design, but also exhaustion of university emails (invites may have instead been ignored). However, given that the response rates were concentrated on one specific demographic and was still of substantial number, this may not be an issue (the 8.3% rate is still significantly higher than the target TTS rate).

The TTS 2.0 inverted frame field test results were similarly mixed. While business interest was initially high to distribute, follow through was quite low (only 5% distributed vs 40% agreeing), with a challenge to identify what would be of value to businesses to motivate them to participate. Moreover, professionals and those with higher incomes tend to complete the survey, which is problematic given existing skew in the current TTS results towards higher-income households. However, this may be due to insufficient logistical support for businesses hiring lower-income workers. The agency test, intended to be a proxy for conducting an HTS at larger institutions that were convinced of its value, saw disappointingly low participation. The biggest issue responsible for such low participation was the need for a long lead time to get approval, but there was a general unwillingness to make a serious effort for widespread distribution.

Prospects: Given the above discussion, the use of inverted sampling would be the best as a compliment in a multiple frame sampling approach. A post-secondary survey can be used to improve population representation by filling the gap of student-aged respondents (particularly those living on campus). Likewise, an inverted frame method can target specific businesses with demographics underrepresented, or geographic areas under-represented. The issues experienced with the field test indicate the need to build out relationships with agencies, institutions and companies ahead of time, providing more information and support. Call-centre interviewers can be re-tasked as on-premise support for interested companies. Finally, the survey should focus on medium-to-large-sized businesses and institutions to maximize the ability to maintain relationships over successive surveys.

4.1.1.5 PANEL-BASED FRAME

A panel-based frame is formed from respondents who are recruited and repeatedly interviewed over time. Its goal is to track their travel behavior changes with time. Multi-day/week surveys are sometimes considered as short panels. A notable example of panel-based frame is observed in the Dutch Mobile Mobility Survey, where the *Longitudinal Internet Studies for the Social Sciences (LISS)* panel was used to sample respondents for the smartphone survey. A similar smartphone survey in the US used the probability-based online panel *KnowledgePanel*. Recruitment for the smartphone survey was carried out through an address-based frame, allowing for more CPO households to be covered than RDD sampling [**2015 Smartphone, 6.3**].

Advantages: The greatest advantage of panel-based frame is that it lends itself to the conduct of longitudinal studies by allowing changes in travel behavior to be tracked over time. A panel dataset is better-suited to monitor changes in travel activity due to individual attributes [**2015 Continuous, 2.4**].

Disadvantages: The use of panel frames is relatively rare in transportation planning owing to high panel construction and maintenance costs, high respondent burden and unwillingness of agencies to wait for the results of a long-term panel survey to materialize [**TAC II, 2.2.6**]. It also suffers from representation issue. Despite striving to represent the target population, inclusion can be highly subject to bias, impairing the representativeness of the frame. This is especially true for sample selection from web panels [**2016 Sample Frame, 5**]. Similarly, when forming a representative internet panel, survey administrators need to ensure that certain demographics are neither over nor under represented. Nonetheless, the probabilistic sampling technique to select panel members is subject to self-selection bias [**2015 Web, 2.1.2**]. Moreover, anti-spam legislation and the lack of an existing, comprehensive list of emails are key impediments to carrying out a web survey using a panel [**2016 Sample Frame, 5**].

Prospects: From the above discussions it is evident that panel-based frame is ideal for gathering data required for developing dynamic travel behavior model. However, it is not suitable for large-scale cross-sectional household travel surveys like the TTS owing to high cost, high respondent burden, recruitment challenges and biased results.

4.1.1.6 MULTI-FRAME APPROACH

Based on the critical review of different closed frames presented above, it is evident that each has its own pros and cons. In terms of population representation, none of the sample frames, except the address-based frame, can be considered to be potentially complete. While the landline frame usually has relatively high response rates through CATI surveys, it does not include non-landline users. On the other hand, the cell phone and the company/institutional frames are well-suited to represent certain hard-to-reach segments of the population, but are not representative of the entire population as a whole. Panel-based frames are not suitable for large-scale household travel surveys mainly due to sampling bias, expensive panel construction and maintenance, high response burden and respondent recruitment challenges. Thus, address-based sampling is often considered the only viable means of contacting and recruiting a random sample from the population, including members of "difficult-to-reach populations" [**2017 Multiple Frame, 2**]. However, the address-based frame suffers from low response rate.

As a result, the logical solution is to adopt a multi-frame approach when conducting an HTS. This allows a survey to overcome the negative aspects of one frame by leveraging the positive aspects of the others to improve overall population representation. This is seen in the 2016 iteration of the TTS which used multiple sample frames (consisting of address/phone, address-only, and phone-only) to alleviate underrepresentation due to a decline in landline use. This resulted in a higher proportion of apartments, 1-to-2-person households, and 20-39 and 60+ year-olds in 2016 compared to 2011. RMSE values show that the 2016 TTS has better representation than 2011 with the GTHA [**2017 Multiple Frame, 6**].

Ideally, when multiple frames are used to sample respondents, it should be backed up with a multi-mode survey to improve response rates. This is because, traditionally, respondents from different sample frames have been found to prefer different types of modes. As mentioned earlier, 2016 TTS respondents from the address-only frame were more likely to complete the survey via the web, while respondents from the other two groups were more likely to participate over the phone [**2017 Multiple Frame, 8**]. Such mixed mode surveys need to be combined with differences in recruiting method to gain the desired increase in participation rate. However, survey mode bias should be accounted for. Techniques for reducing survey mode bias can be found in [**Final, 6.1**].

A key issue of concern in using multiple sample frames for the same survey is the potential double-counting of sampling units. Analysts need to be aware of the implications of such overlap and should adopt appropriate measures to account for it [**2016 Sample Frame, 9**]. For joint landline and cell-phone frames, the **2015 Landline Report** discusses two different approaches to handle the overlap: the screening approach and the overlap approach. In the *screening approach*, interviewers terminate interviews with cell phone respondents who have at least one landline phone in the household. This requires the interviewers to contact the respondent once again on their landline, which raises the survey cost. Alternately, the respondents can be asked at the beginning of the survey if they (or any other member of the household) have already participated in the survey and either conduct or terminate the interview accordingly. In the *overlap approach*, the interview is conducted regardless of the frame from which the respondent is selected (landline or cell). This approach is typically advantageous if there is a fundamental assumption that the probability of a respondent being randomly selected in both frames is negligible. However, such an assumption might not be applicable for large-scale surveys like the TTS. In this case, without a weight adjustment, the estimate of households in the overlap will be double the appropriate estimate. The 2009 Minnesota Health Access Survey, which used a dual landline and cell-phone frame, adjusted weights in sample overlaps by using composite weighting; i.e. multiplying the weights in one sample by a weighting adjustment factor λ, and multiplying the weights in the other sample by $(1-\lambda)$. Refer to [**2015 Landline, 2.2**] for details on the weighting factor calculation.

Based on the critical review presented above, it is clear that using multiple sample frames is the way forward for the core survey. Such a composite frame has the potential to representatively sample the survey population if backed-up by proper recruitment techniques and use of proper survey modes. However, the potential double-counting that may result from this needs to be addressed.

4.1.2 Open Frames

An open frame does not explicitly list the potential survey samples. Generally, this frame is used when no comprehensive list exists for the target population or where the method of recruitment does not allow for a closed set of potential respondents. Examples of open frames include social media, transit schedule/run and intercept, with social media being the most promising one. At present, social networks are used by a large segment of the population for online interaction and information access. Almost 70% of Canadians say they use social media, with Facebook as the most popular social networking site. The use of these social networks, however, is not uniformly distributed across the population; key differences are observed between gender, ages, dwelling locations and linguistic group. For example, a 2009 study among Canadians aged 18 years and older by Ipsos Reid showed that women (59%) are more likely to have a social network profile than men (52%). Such non-random nature of the frame is the main reason behind its limited application for assessing transportation behavior. **[TAC PII, 4.5]**

Advantages: The main benefit of using social networks as a sample frame stems from the fact that these networks can be used to recruit respondents for web-based travel surveys in a faster and cheaper way and with less assistance. Moreover, social networks can be mined for planning relevant information, for example, locational/trip-making information and comment or complaints about traffic/transit.

Disadvantages: This frame, however, has several drawbacks. The most serious among these is the introduction of sampling bias, since only people connected to the network have a non-zero probability of getting sampled [**TAC PII, 4.5**]. Social media can be biased towards certain demographics, but full research has not been done to characterize these demographics (Murphy, et al., 2014). Currently, researchers are only using social media to obtain qualitative insights [**2015 Smartphone, 8.2.4**]. Little progress has been made to show how data collected through social media can represent the general population – so far only non-probability samples have been obtained. Another issue of using social networks is that the sample frame cannot be controlled. Moreover, there are security issues of hacking, data corruption and email blockages while transmitting data through the web or network [**TAC PII, 4.5**].

Prospects: In light of the above facts it is evident that currently open frames like the social network is mostly applicable when seeking to construct "snowball" samples for exploratory work. In snowball sampling/chain referral sampling/respondent driven sampling, an invitation to participate is first sent to a convenience sample that acts as seed for recruitment. This method, however, can yield large samples (based on the recruitment procedure and some luck), so the process is non-probabilistic and deals with ill-defined populations. Hence this sample frame is not generally recommended for household travel surveys whose main aim is to represent the travel behavior of the entire population. **[TAC PII, 4.5]**

4.1.3 Recommendations for sample frame of 2021 TTS

Owing to the growing incomprehensiveness of the landline frame, the core survey of the 2021 TTS should adopt an address-based multi-frame approach. The frames used should comprise of address & phone (landline), address-only and phone-only frames similar to the 2016 TTS. The phone-only sample frame can be derived from RDD and verified cell phone listings. It is important to include this frame in the core survey since the socio-demographics and trip patterns of CPO households are different from the general population. However, to improve the response rate of the frame, pre-notification by SMS can be considered.

Core extension surveys [**Final, 3.3.2**] should use the same sample frame as that of the core. This may be considered as a panel-based frame, where the respondents for the core extension survey are sampled directly from the core sample. On the other hand, core-filling satellite surveys should be based on address-based frame or company/institutional frame depending on their end goal. Address-based frames would be preferred if the aim of the core-filling survey is to reduce geographical gaps, whereas company/institutional frames would be ideal for reducing demographic gaps. For example, StudentMoveTO can be used for improving the representation of student-aged respondents (particularly those living on campus) and the inverted frame can be used to target specific businesses with underrepresented demographics, or underrepresented geographic areas.

In terms of the other satellites, linked satellites should use panel-based frames constructed from the core sample, similar to the core extension survey. However, it would target a specific sub-population of the core. As for the independent satellites, frame selection would vary depending on the survey purpose.

4.2 Sampling Method

A sampling method is the process of drawing a sample of units from a frame. Choosing the proper sampling method is crucial to the interpretation of survey results. To make statistically valid inferences about a population's attributes or behaviors from a sample of respondents, drawing a representative sample using the appropriate sampling method is a prerequisite. The selected sampling method should be both efficient (precise) and unbiased (accurate). This section presents a critique of the common sampling methods used in household travel surveys and thereby recommends suitable methods for the various core-satellite surveys.

4.2.1 Overview of common sampling methods

A sample of respondents can be drawn from a given sample frame by any of the following sampling methods (detailed in [**TAC PII, 2.2.2**]):

- **Simple random sampling:** This is the standard/base method where sampling units are randomly selected from the sample frame, so that no bias is introduced into the sampled set.
- **Sequential sampling:** This method assumes that the sample frame is randomly ordered, so that the list can be sequentially (rather than randomly) sampled, which increases the efficiency (and simplicity) of the sampling process.
- **Stratified random sampling:** This is a method of controlled and over-sampling of important target sub-populations. Such oversampling may be necessary if the target sub-population is difficult to observe in statistically useful numbers through a simple random sample without needing an excessive sample size. In this method, population is stratified into a set of mutually exclusive and collectively exhaustive categories and each category is assigned its own sampling rate.
- **Cluster sampling:** This is the cost-effective way of surveying sampling units for which a sample frame is difficult to directly construct. Household-based surveys are implicitly cluster samples of individual persons.

4.2.2 Common sampling methods adopted in household travel surveys

The commonly used sampling methods in household travel surveys include geographically stratified random sampling, disproportionate stratified sampling and choice-based sampling. This section describes each of these methods by highlighting their applicability, the associated advantages and disadvantages and methods of overcoming some of the drawbacks.

The sampling method adopted for most large-scale HTS is the geographically stratified random sampling technique. This method is used to sample from an address-based frame to permit differential sampling rates by geographic jurisdiction. It thus ensures adequate geographic coverage by the overall respondent sample. In this method, first stratification of the entire survey area is done by city, planning district, or other appropriate geographic jurisdiction (the TTS, for example, uses stratified random sampling by planning district). A random sample is then selected from each stratum/group. The sample size of each stratum is proportionate to the population size of the stratum.

Disproportionate stratified sampling is adopted in HTS when adequate sample units (respondents) from certain geographic jurisdictions cannot be ensured by stratified random sampling. Here the sample size of each stratum does not have to be proportionate to the population size of the stratum, but should be adequate to represent in statistically useful numbers. Weights can be developed to account for biases introduced by such disproportionate sampling scheme. In-person surveys mostly adopt this sampling technique owing to better access to respondents within a geographically constrained area. The in-person pilot survey conducted under the TTS2.0 project adopted this sampling strategy to survey respondents from CTs that were underrepresented in the 2011 TTS (particularly for individuals in the 18-34 range). More details on the sampling method can be found in [**2017 In-Person Field, 3.2**].

In choice-based sampling, the population is classified into subsets to be sampled based on the choices they have made. For each of the chosen alternatives, a random sample is drawn of those individuals who chose that alternative. Drawing samples based on choices is easy and less costly and may ensure the drawing of a sufficient number of observations of rarely-chosen alternatives. However, parameter estimation is difficult and requires knowledge of the overall population share. Mixing the choice-based sample with a general sample requires an appropriate weighting scheme [**Final, 7.4**].

4.2.3 Temporal Considerations of sampling methods

The main temporal aspects that need to be considered while determining the proper sampling method for an HTS are the survey observation period, day(s) of the week to be surveyed and whether the survey should be cross-sectional or continuous in nature. These considerations are briefly described here. Details on these and other temporal considerations can be found in [**TAC PII, 2.2.6**].

I. Survey observation period: Most travel surveys collect 24 hours of trip information so as to capture a random day in the respondent's life; however, depending on the survey purpose, the observation period may be shorter (morning peak periods, etc.), or longer (2+ days, one-week, multi-week). While longer periods obviously provide more information, they increase survey cost and respondent burden.

II. Day(s) of the week to be surveyed: Most travel surveys focus on weekday travel (with occasional emphasis on weekday peak-period travel). However, weekend travel has very different patterns, which stresses the transportation system in different and important ways. As such, activity-based travel models are now paying more attention to the interplay of weekend and weekday travel decision-making. This investigation has made weekend travel information collection necessary. Collecting both weekday and weekend data through the core survey would require substantial increase of the sample size necessary for just weekday collection. Further increase of an already large sample size (5% in the case of the TTS) might not be feasible from survey cost and implementation perspectives. An alternate solution might be collecting weekend trip diary for a smaller sample through a core extension survey using the same sample frame as the core. This would ensure a representative sample which can be expanded to reflect the overall weekend trip behavior of the population.

III. Cross-sectional vs. Continuous surveys: A repeated cross-sectional survey allows *overall* behavior within the system to be tracked over discrete points in time. From a practical standpoint, sample responses are generally collected over a period of time (e.g. several months in fall in the case of the TTS). Then, the data is temporally aggregated to represent the travel pattern on a "typical" fall day. Such temporal aggregation in a cross-sectional survey, however, tends to average out variations in daily travel pattern. Moreover, a cross-sectional survey does not allow the comparison between short term and long-term trends. Another drawback is the loss of experienced staff and knowledge during the gaps between the surveys. Details on these disadvantages can be found in [**2015 Continuous, 2.1**].

On the other hand, in a continuous survey, smaller samples of respondents are surveyed on an ongoing basis. Thus, it has the potential to capture global evolution of mobility behavior over time. Assuming that statistically adequate OD matrices can be generated from the continuous survey data, the updated OD matrices can reflect the differential growth of mobility over time. The survey can also capture weather/seasonal effects on travel behavior. The continuous nature of the data may permit the use of sophisticated models, such as process models, to investigate dynamics and adaptation of travel behavior. Short- and long-term impacts of transport policies may also be assessed; moreover, massive swings in budget and staffing can be avoided. Refer to [**2015 Continuous, 2.2**] for more advantages of continuous surveys.

There are, however, many drawbacks associated with continuous surveys. Continuous surveys are not necessarily cheaper than cross-sectional surveys – the cost is simply distributed over a longer time period. In addition, if a cross-sectional sample size of 5% is dispersed over 5 years, this would result in a 1% annual sample size, too thin to statistically support the annual updating of OD matrices. Cools et al. (2010) concluded that an OD matrix reproduced from a sampling rate of 1% has a MAPE of 19%. This is for peak period auto-mode commuter-only travel; a general peak period OD matrix for all trip purposes would have an even higher MAPE. Capturing weather/seasonal variation would require an even larger sample size to be statistically adequate. Real world trials have shown this reduced yearly sample size to be an issue. The fall sample of the Montreal continuous survey (which split its typical 4% to 5% cross-sectional sample size over a 5-year period) was found to be too thin to measure significant annual variations at the sub-district level, making it difficult to capture seasonal trends. For more details, refer to [**2015 Continuous, 4.2**].

Pooling samples over years so that a sufficient sample size is available for modelling is one approach that can be used. It, however, might hamper the data quality as the temporal variability within the data may introduce noise. Furthermore, it might become difficult to fit the annual fall results with the existing 5-year trends of TTS as happened with the Montreal continuous survey results [**2015 Continuous, 4.2**]. It would not be possible to determine accurate weighting factors since control totals from census are available once every 5 years. Using imputation methods to fill in missing values might be even more problematic.

Based on the above arguments, it is evident that converting the current cross-sectional TTS into a continuous data collection effort by simply splitting its sample size over a period of 5years would not yield desirable results. Instead, the potential of numerous high-resolution passive data sources (e.g. Smartcard, Bluetooth/Wi-Fi, Cellular etc.) available at present might be exploited in this regard. As mentioned earlier [**Final, 2.1.3**], these passive data sources provide continuous data over the year. The travel information extracted from these sources can be used to continuously update TTS data using proper data fusion techniques (detailed discussion on this can be found in **Final, 7.4**). This would allow for changes in mobility and travel behaviour throughout the period to be captured while maintaining data quality and consistency in the current surveying approach.

4.2.4 Recommendations for sampling method of 2021 TTS

Based on the critical review of different sampling methods presented above, the following recommendations can be made with respect to the sampling methods for the different components of the 2021 TTS:

- For the core survey, geographically stratified random sampling technique should be adopted.
- Respondents for the core-extension survey should be sampled from the core sample according to a predefined sampling rate using the simple stratified random sampling method.
- For core-filling surveys, disproportionate stratified sampling may be appropriate.
- Linked satellites should randomly sample potential respondents who belong to the targeted group using the list of individuals who showed interest to participate in future surveys.
- Depending on the type of population to be surveyed, a choice-based sampling method may be more appropriate for independent satellite surveys, such as active mode or transit on-board surveys.

For the core survey, it would be best to retain the current repeated cross-sectional nature rather than shifting to continuous data collection owing to the following reasons:

- A shift from cross-sectional to continuous surveys with the current sample size will result in lower data quality.
- The sample size to support the shift would be too large to be practical.
- Leveraging available and emerging passive data sources with appropriate fusion techniques would instead allow for capturing changes in travel patterns while maintaining data quality.

4.3 Sample Size Requirements

Sample size determination is a very crucial step of survey design. While the precision of population estimates derived from survey samples always improves with increased sample size, there is a point at which increased sample size is not cost-effective [**TAC PII, 2.2.3**]. In general, a three-way trade-off exists in every survey among sample size, survey complexity and survey cost, which complicates target sample size determination. When considering a single objective variable, the sample size calculation procedure is fairly straightforward [**2015 Sample Size, 4**]. However, for a multi-objective household survey, it can be quite complicated. Here, the sample size can be affected by purpose, population representation, variability of key variables, tolerance of errors, and desired confidence limits; however, more commonly the final sampling rates are based on budgetary constraints [**2015 Sample Size, 4**].

4.3.1 Approaches to calculate sample size

Over the years, different approaches have been proposed to calculate sample size. Smith (1979) argued that, within the traditional four-stage model, trip distribution is the critical step that constrains (and ultimately increases the minimum) sample size requirement. He found that for zones with fewer than 1,100 trips between them, at least a 4% sample is needed for a 90% confidence interval (CI) and 25% margin of error (MoE) [**2015 Sample Size, 4**]. More details on this approach can be found in [**2015 Landline, 4.2**]. In the 2007/08 Washington Transportation Survey, the sample size requirements were reduced by isolating hard-to-reach groups prior to the survey and over-sampling the corresponding strata [**2015 Landline, 4.1**]. A similar approach was adopted in the 2010-2012 California Household Travel Survey which selectively oversampled addresses from the census tract with high concentrations of hard-to-reach groups, and these address-based samples were supplemented with 'targeted' listed residential samples [**2015 Landline, 4.2**].

Strata sizes tend to be determined by the proportion of each stratum within the general population. Harder-to-reach groups may be oversampled based on how under-sampled they were historically [**2015 Landline, 4.3**]. Kim and Mahmassani (2014) suggest three approaches to determine strata sizes – optimal allocation for mean, proportional allocation, uniform allocation; optimal allocation was found to be the best to predict travel times, although this approach is still theoretical [**2015 Landline, 4.3**].

4.3.2 Sample sizes used in practice

The sample sizes adopted in different HTS vary widely across agencies. Surveys aiming to produce statistically significant OD matrices at the traffic zone levels tend to go for larger sample sizes, sampling around 5% of the population. On the other hand, surveys which have a main purpose of developing travel demand models tend to go for smaller sample sizes of about 1% of the population. Although there is no consensus on selection of sample size for HTS, there is a trend that is inclined towards continuous surveys (with smaller sample sizes) [**2015 Sample Size, 3**].

TMIP (1996) recommends a minimum sample size of 1% for large urban areas and 10% for small suburban areas. However, NCHRP (2008) highlights that even a large sample size may not be sufficient to achieve the stated objectives, if the representation of the behavior of interest is low [**2015 Sample Size, 2**]. In the North American context, the general trend of sample sizes varies widely between Canadian and the US surveys. While the majority of HTS in Canada have sample sizes between 2-5%, nearly all US surveys have sample sizes less than 1%; however, US surveys are more proactive in adopting advanced technology, e.g. GPS [**2015 Sample Size, 3**]. Conversely, a survey of Canadian transportation agencies conducted in 2012 revealed that many of the respondents are still concerned with survey sample sizes being too small to analyze subsets of trips (e.g. transit, cycling, pedestrian) [**TAC PV, 5.2**].

4.3.3 Case study of the GTHA

Acknowledging the fact that small samples tend to yield insufficient data for long-term analysis and disaggregate travel demand models, an empirical investigation was conducted under the TTS 2.0 project to assess the representativeness of large-sample HTS. As a case study, data from the 2011 TTS was used to evaluate its ability to represent the target population (obtained from census data). For details on the case study, refer to [**2015 Sample Size, 4**]. It was found that the 5% sample data represented its target population with an 80% accuracy margin. Some areas, however, had an insufficient number of data points to yield desired CIs and MoE. To overcome this problem, the study recommends a core-augment approach of sample size determination for the TTS [**2015 Sample Size, 5**]. Using the 2011 TTS data, sample size requirements for the proposed attribute-based augment sample were calculated, based on the method originally proposed by Smith (1979) [**2015 Sample Size, 6**]. A minimum 4% sample was recommended for the TTS using stratified random sampling, with additional augment samples for individual regions/cities [**2015 Sample Size, 7**].

4.3.4 Recommendations for sample sizes for the 2021 TTS

For the core survey, the current sample size of 5% of the population is recommended. Even though shifting to a stratified random sample of 4% with additional augment samples for individual regions/cities may be helpful to gather sufficient data from hard-to-reach or low-population zones, it may cause administrative difficulty when conducting the overall core survey. Rather, the core-filling survey is designed within the core-satellite approach to overcome this problem. As the core-filling surveys generally employ cluster sampling (with full-institution email-outs), setting sample size is less of a concern than the method to fuse their data with those of the core survey.

Since the core-extension survey will randomly sample from the core sample, its sample size will be a fraction of the overall core sample. The exact sample size of this survey will be determined by the specific travel data to be collected and its application. This will dictate the sample size required to adequately capture the specific travel behavior (in statistically useful numbers).

4.4 Sample Recruitment and Incentives

In most surveys, the majority of non-respondents arise from a failure to recruit them to the survey. This results in extra costs and introduces significant non-respondent bias in the data. Contact/recruitment methods often depend on the type of survey being conducted, but include mailed letters, telephone calls or e-mail contacts for closed frame samples and intercept or social media recruitment for open frame samples. The most effective strategy is the combined use of multiple response-inducing techniques, that is contacting and reminding through both mail, email, telephone, etc. *and* offering different modes of response or choice of modes at different stages. [**2015 Smartphone, 8.2.1**]

The survey of Canadian transportation agencies conducted in 2012 revealed that for household travel surveys, initial contact method has been mostly letter or phone, whereas phone is mostly used for follow-up [**TAC PV, 5.2**]. Selecting the appropriate recruitment technique is important as it may have substantial influence on participant responses [**2015 Smartphone, 8.2.3**]. As such, selecting the proper recruitment technique is essential not only for achieving the target sample size, but also for ensuring data quality and representativeness.

4.4.1 Common sample recruitment techniques for closed frame samples

Landline frame: Respondents from the landline frame are usually recruited through an advance letter mailed to each of the selected households, mentioning the date of the phone-call (for CATI) or the secure web access code and the study webpage URL (for online surveys).

Address-only frame: Households receive a notification letter. Next, depending on the survey mode, they can either complete the survey online (using the secure web access code and the study webpage URL provided in the notification letter), by telephoning a toll-free/local number (provided in the notification letter), or by completing a mail back survey (which is mailed out a few days after the notification letter)

The advance letter sent to all selected households is a critical item for recruiting from both landline and address based frames. It encourages a high response rate and, for CATI, minimizes the time interviewers need to spend explaining the survey. Official signatures in the letter give legitimacy to the survey, thereby increasing the potential of participation. Also, an official government envelope ensures that it is not treated as junk mail.

Cell-phone frame: Currently, individuals are 'cold-called'. Those who refuse to complete via cell phone are offered the option of completing the survey online and are provided with their secure web access code and the study webpage URL. Recently, advance texting is being considered to inform the cell phone user of the survey so as to increase response rate (Dal Grande, et al., 2016). Results indicate that sending a pre-notification SMS is effective in improving participation in population-based surveys. Response rates were increased by 60% and cooperation rates by 79%.

Institution/company-based frame: Recruitment is done using email lists kept by the employer or school. This email list, being close to comprehensive, provides an easy means of reaching respondents. On-campus recruitment has also been used for post-secondary students [**2017 Core Satellite, 4.3.1**], and a similar on-site approach may be viable for other institutions or businesses.

Panel-based frames: Random sampling from pre-existing registers is commonly used to form probability-based web panels [**2016 Sample Frame, 5**]. Recruitment can also be done through professional survey firms, cold-calling, mailbox drop or using electronic circulation lists. Social media and face-to-face recruitment are generally used for forming non-probability-based panels.

4.4.2 Common sample recruitment techniques for open frames

Roadside intercept: This involves intercepting and recruiting people during the course of their travel. To ensure probabilistic sampling, every n^{th} road user is stopped at intercept point and handed a letter containing the survey information.

Social media/Crowdsource campaigns: Methods for recruiting using social media include creating a group, on Facebook for example, and targeting specific groups and users of interest. It is an easy way of reaching a specific demographic, but does not provide a probabilistic sample. Pay-per-click ads can be used to recruit a more diverse set of respondents and can be used to do a targeted campaign [**2015 Smartphone, 8.2.4**]. Crowdsource approaches for recruitment involve publishing ads on traditional media, social media and blogs or disseminating the survey website URL among the members of different organizations and advocacy groups through email invitation or fliers at events. The CityLogger campaign, one of the TTS 2.0 pilot projects, used crowdsourcing as a method of recruitment, in addition to sending email invitations randomly to 2016 TTS respondents who agreed to be contacted for future studies [**2017 Smartphone Field, 1**]. Out of a total 1703 respondents, 389 were recruited through crowdsource; however, the demographics of the crowdsource respondents were much different from those recruited through email invites [**2017 Smartphone Field, 4.1**]. For details on the demographics and travel behavior of the crowdsource respondents, refer to [**2017 Smartphone Field, 4.2.1 & 4.2.2**]. The project concluded that while the crowdsourcing recruitment method is promising, it is not a good way to capture a representative set of the population.

4.4.3 Respondent Contact and Recruitment Challenges

The contact and recruitment of respondents for household travel surveys face numerous challenges. For surveys conducted through the phone, telemarketers and increasing use of call screening services pose a challenge to recruit households through phone directly. This is complicated by legal issues such as being in compliance with restrictions on calling cell phones (if any exist), text messaging, and spam. To overcome these challenges, telephone interview surveys now send invitations by mail prior to the interview to explain the objective and significance of the survey, and specify the targeted interview day [**TAC PII, 2.4.2**]. Prior notification letters have proven to increase response rates, especially of households living in single family housing units. It is, however, difficult to reach apartments by mail as apartment numbers are not commonly listed in sample frames. Moreover, highly mobile apartment dwellers are difficult to contact by mail.

For face-to-face recruitment for in-person surveys, the main challenge is the security concern for both the respondent and the interviewer; this method is the most susceptible to disruptions and crime [**2017 In-Person Field, 2**]. Face-to-face recruitment requires trained interviewers and may require multiple attempts to contact respondents [**2017 In-Person Field, 2**]. For example, in the 2017 In-Person Pilot Survey conducted under the TTS2.0 project, if no one was home or they refused to participate in the survey, interviewers left a second letter that contained a survey code [**2017 In-Person Field, 3.3**].

For crowdsourcing/social media recruitment, an important challenge is that the popularity of different social media websites rises and falls over time. In addition, demographics of the users of each website vary. Moreover, individuals who are less active may be missed or systematically under-sampled. This makes the results of data collection biased towards the heaviest users. Other challenges of recruitment through crowdsourcing/social media can be found in [**2015 Smartphone, 8.2.4**]. On the other hand, several techniques for making crowdsourcing an effective recruitment method have been discussed in [**2017 Smartphone Field, 5.2**]. The report suggests that greater lead time must be given to allow for a campaign to build and partners to be brought on board. Additional time is also needed if any advertising is to be bought on transit vehicles or billboards. Also, efforts should not be focused too narrowly on one date or event, instead aiming to have multiple points at which the story can be picked up on, with important milestones and cross-promotional opportunities in addition to a launch event.

4.4.4 Use of incentives in travel surveys

Generally, incentives are not used for large-scale travel surveys; instead, they are offered for smaller-scale surveys with considerable respondent burden. Mixed results on the cost-effectiveness of incentives on response rates are reported in the literature. The results vary with the specifics of the survey and the population being surveyed. Advance incentive has been found to be more effective than raffle draws or gift certificates [**2015 Smartphone, 8.2.3**].

Incentives are sometimes also offered to interviewers to encourage the proper execution of surveys. This was investigated in the 2017 In-person field test which offered interviewers $5/completed household survey (all demographic and mobility tool information completed for all household members) plus one travel diary. Interviewers were also offered an additional $2.50 per additional completed travel diary [**2017 In-Person Field, 3.5**].

Incentives and messaging are particularly effective to motivate people to participate in smartphone-app based surveys. The 2017 Smartphone field test offered incentives to justify the additional concerns regarding the privacy for installing an app that collects traces of every travel made and the drain on phone battery [**2017 Smartphone Field, 2.3**].

4.4.5 Recommendations of sample recruitment and incentive for the 2021 TTS

For the multi-frame core survey of the 2021 TTS, it is recommended that households from the landline and address-based frames are recruited through advanced/pre-notification letter, whereas the cell phone-based sample is recruited through advanced texting. Respondents for the core-extension survey may be introduced to the survey immediately after the completion of the core questions. For the core-filling satellite survey, recruitment can be done using the email list available with the institution; on-site recruitment can also be helpful in this regard. On the other hand, for the linked satellites, recruitment should be done using the email or phone list of core respondents who showed interest to participate in future surveys. Finally, the recruitment method for the independent survey will depend on the end goal of the survey. In addition to these methods, independent surveys can adopt innovative and emerging recruitment techniques like roadside intercept and crowdsourcing, given that a proper data fusion technique is applied to integrate the collected data with the core. Incentives should not be included in the core survey, as it may cause self-selection bias in the sample; however, they can be considered for satellite surveys if the respondent burden is considerably high.

5 SURVEY MODE SELECTION

A critical component of the survey design process is the choice of survey mode. The survey mode, not to be confused with the survey instrument, refers to the method through which a survey is implemented. Examples of survey modes include paper questionnaires, smartphone applications, and web-based interface. Each survey mode has its own set of strengths and weaknesses, which can affect the quality of the data that they collect. Similarly, there are applications and contexts in which some modes are inadequate while others thrive. These strengths and weaknesses must be taken into consideration when selecting a survey mode in order to ensure that the right tool is chosen for the job.

This chapter examines the characteristics of four different survey modes – computer-aided telephone interview (CATI), web-based surveys (CAWI), smartphone surveys, and in-person surveys (CAPI). The examination of these modes centres around five aspects of each survey mode:

- The pros and cons of using each mode,
- The sampling frames that are typically used,
- A general profile of the respondents obtained using each mode,
- Applications for which each mode is appropriate, and
- Typical applications of each mode

Additionally, the characteristics of multimodal surveys (i.e. the use of multiple modes to conduct a survey) is also discussed.

5.1 Computer-Aided Telephone Interview (CATI)

The computer-aided telephone interview (CATI) is characterized by the use of the telephone to contact prospective respondents and to solicit responses to survey questions. When using this mode, trained interviewers are responsible for contacting respondents, administering the survey questionnaire, and recording the responses. Respondents are asked to recall the trips that they made on a specific date, which is then recorded by the interviewer. In the case of household travel surveys, a single household member (typically someone who meets an age criterion) is asked to recall the trips made by all members of the household. This survey mode rose to prominence in the 1970s when the cost of conducting a telephone survey fell to an extent that made it more attractive than in-person surveys **[2017 In-person Field, 2.2]**. One of the most attractive aspects of CATI stemmed from the prevalence of landline telephones. This popularity meant that the sample frames used in CATI surveys provided a reasonable degree of coverage of the survey area **[2016 Sample Frame, 2.1]**. For a while, CATI was the mode that was most commonly used for large-scale travel surveys **[2015 Landline, 1]**. Although its dominance among survey modes eroded over the years, the computer-assisted telephone interview (CATI) is still widely used, although generally in conjunction with other modes.

Advantages: The most significant advantage of using CATI as a survey mode stems from the presence of the interviewer. Having trained interviewers walking respondents through their questionnaires allows for more complex questions to be asked without placing an inordinate amount of burden onto the respondents and allowing for clarifications as needed, potentially improving data quality. The use of CATI allows respondents to focus on answering questions and transfers the responsibility of navigating the survey interface to the interviewer. The computerized nature of the data collection process also allows for monitoring of the input data, which facilitates real-time quality assurance. Additionally, the ubiquity of phones (i.e. landlines and cellphones) helps create the potential to contact most, if not every, member of the target population. Despite their growing obsolescence, CATI surveys still have value, although they are not without their issues.

Disadvantages: The disadvantages associated with the use of CATI to conduct a survey can be broken down into two broad categories: bias and representation. The use of CATI to conduct a survey has its own unique impacts on data quality, i.e. its own set of survey mode biases, which is discussed in more detail in Chapter 6. When conducting a survey using CATI, the potential for interviewer bias must be carefully examined because of the inherent person-to-person interactions that takes place. The presence of another person, even a stranger, when completing a survey can result in respondents providing responses that are more socially acceptable than they would otherwise be. Survey results can also be affected by the use of proxies to collect data on behalf of other members of the household. The use of proxies can result in the underrepresentation of short and non-motorized trips **[2015 Landline, 1]**. In an attempt to reduce proxy biases, the "callback" method, wherein other household members are called to provide responses on their own behalf, has been used. A full discussion of proxy bias is presented in [**Final, 6.4**]. CATI surveys also tend to over-represent older members of the population, even when used as part of a multimodal survey, and tend to dissuade larger households from participating.

Selection and Use: Although CATI is no longer considered to be the default survey mode of large-scale travel surveys, CATI is still valuable as one component of a multi-modal survey. This mode remains a fairly effective option to collect information from older members of the population, and the presence of an interviewer helps ensure that the required level of technical proficiency is less than that of other survey modes. Moving forward, CATI should be used for surveys:

- In which landline penetration rates among the target population are high,
- Where a sample frame of both landline and cellphone numbers are already available, or
- That offer respondents the option to choose their survey mode

In addition, further work must be done to address the shortcomings of CATI surveys. This should include an investigation into methods to harmonize the inherent biases in data collected using multiple modes. Furthermore, attempts to form a representative sample frame of phone numbers (both landline and cellphone) should continue.

5.2 Web-Based Surveys (CAWI)

As the ability of CATI surveys to provide an adequate representation of a target population declined, surveyors and researchers began to experiment with the use of other survey modes that could supplement or replace CATI. One survey mode that has emerged and risen to prominence is the web survey. The growing popularity of web-based surveys can primarily be attributed to the increases in internet access that partially coincided with the decline in landline ownership. Web-based surveys are characterized by the self-reporting of information through a web browser and the fact that its ability to collect information is limited to households with internet access. Web surveys tend to elicit lower response rates than other survey modes, and tend to have high start-up costs but lower marginal costs, while allowing data to be available almost instantaneously. The efficacy of web surveys tends to be contingent on the design of the survey, as the quality of the collected data are affected by the design of the interface, the formulation of the questions, and the validation of the information provided by respondents.

Within the Canadian context, the utilization of web surveys in household travel surveys is on the rise. In the Greater Golden Horseshoe (GGH), the TTS began offering its invitees the option to complete the survey over the phone or through the web, and this continued in the 2016 iteration of the survey. Web surveys have also been used in conjunction with smartphone-based surveys, typically serving as a means of providing a pre-survey questionnaire and facilitating the validation of inferred trip information. Additional information can be found in [**TAC P2, 4.2**].

Advantages: One of the primary advantages of using web-based surveys is their potential to improve the quality of the data that they collect. Compared to CATI surveys, the anonymity of web-based surveys can help to address social desirability bias by increasing the chance that respondents answer questions in a manner that accurately reflects their behaviour [**2015 Web, 3.1**]. Allowing respondents to complete the survey anonymously may also encourage and improve participation if sensitive information (e.g. income) is being solicited. The electronic collection of information also allows data to be monitored in real time, which facilitates the use of logic checks and reminders [**2015 Web, 3.2**] and can result in faster response and collection speeds [**2016 Sample Frame, 5.0**]. The ability to incorporate features that aim to reduce response burden can also have a positive impact on data quality. Features such as auto-correct, auto-fill, and integration with map-based interfaces can all be used to reduce response burden [**2015 Web, 3.3**]. In addition, the integration of map-based APIs can also facilitate the collection of more information (compared to CATI surveys) while maintaining the same level of burden [**2016 Web Design, 5**]. The reduction of burden through the aforementioned means creates the potential to facilitate the collection of data over multiple days [**2015 Web, 5**]. A table summarizing the advantages and disadvantages of using web-based surveys, along with the anticipated improvements and impairments over time can be found in [**TAC P2, 4.1**].

Disadvantages: Although the design of a web survey can have a positive influence on respondents, a poorly designed survey can have the opposite effect. The design of the survey interface can have either a positive or negative impact on the responses obtained through the survey [**2015 Web, 3.2**] as well as the attitudes towards the survey [**2016 Web Design, Sec. 2**]. This issue speaks to the need for survey administrators to ensure that their survey is able to accommodate respondents of all aptitudes. The learning curve that the utilization of web surveys imposes onto respondents may affect the profile of web survey respondents, which tends to differ from that of surveys conducted using other modes [**2015 Web, 3.1**]. The relative convenience of web surveys may be offset by the additional burden experienced by those who are not web-literate [**2015 Web, 3.1**]. Consequently, care must be taken to ensure that the design of the survey interface does not affect the information provided by respondents, so as to reduce measurement bias. Clarity and user friendliness are key because all information is self-reported [**TAC P2, 4.2**]. As previously mentioned, web surveys can only be completed by households with internet access, which may make the results obtained by using this mode susceptible to sampling bias [**2015 Web, 2.1**]. The use of this mode also has the potential to introduce proxy bias [**2015 Web, 4**], although the fact that the questionnaire is available in writing can help reduce the frequency with which responses are provided by proxy. In general, web surveys tend to produce low response rates [**2015 Web, 1.0**], which may stem from lingering privacy concerns [**2015 Web, 2.2**] or the preference to use other modes.

Despite the growing popularity of web surveys, they are far from being able to assume the mantle of the default mode for large scale travel surveys that was relinquished by CATI surveys. When used on their own, web surveys tend to over-represent younger, wealthier males who possess higher levels of education [**2015 Web, 2.1**]. When used in conjunction with face-to-face interviews as part of a multimodal survey, respondents who completed the survey through the web also tend to possess higher levels of education and income [**2015 Web, 3.1**]. This discrepancy was observed in the 2011 TTS, where differences in the average age and trip rate for web and CATI respondents were observed [**2015 Web, 6.2**]. Because of the self-reported nature of nature of web surveys, there is a tendency for respondents to under-report short activities, round travel times, and report a “typical” travel day [**2015 Web, 3.1**].

Selection and Use: Because of the inability of web surveys to provide an adequate representation of the entirety of a target population, it is best if they are used in conjunction with other survey modes for large-scale travel survey. Based on the findings of [**2017 Multiple Frames, 8.0**], the use of web surveys may be appropriate in cases where address-based sampling is used. Web surveys are also appropriate in applications where data will be collected from populations with high levels of internet access, or from populations for whom a comprehensive email list exists. The use of web surveys is also recommended for follow-up surveys that are administered to the respondents of previous surveys who have volunteered to participate in future data collection efforts. Moving forward, time should be spent investigating methods to harmonize survey mode biases in data collected through the web and over the phone to allow for the formation of a single, coherent dataset. Finally, from an interface perspective, care must be taken to include features that allow for easy switching between CATI and CAWI survey modes in multi-mode surveys, as well as capabilities that allow for real-time assistance to those completing the survey.

5.3 Smartphone Surveys

Smartphones have emerged as a new viable mode through which travel surveys can be conducted. To a certain extent, smartphone surveys are the next evolution of GPS surveys. Both offer the potential to collect precise spatiotemporal information on a continuous basis, can include both a passive and active stream, and have the potential to facilitate both real-time and planning applications [**TAC P2, 4.3**]. The added benefit of using smartphones to collect spatiotemporal information is the ability to incorporate the information collected from the phone's other sensors into the data collection process. The use of smartphones to collect data also helps address the issues associated with collecting data solely using GPS devices, namely the urban canyon effect and the need to carry a dedicated GPS logger [**2016 Smartphone Technical I, 3**]. Within the context of travel surveys, smartphones can be used to address the issues faced by more traditional survey modes, such as the under-reporting of trips and the burden associated with having to recall prior trips [**2016 Smartphone Technical I, 3**]. This section discusses the state of practice of smartphone-based surveys and its recommended use in travel surveys.

5.3.1 Advantages and Disadvantages

Advantages: Smartphone-based surveys offer a number of improvements over more traditional survey modes. The main benefit stems from the fact that smartphone survey apps periodically record the location of the device, creating traces of movement. The collection of these traces creates the potential to obtain data that could not be collected through a traditional travel survey, and by extension enables new applications of said data. The collection of these traces, and the inference of trips, helps to capture trips that would have been omitted in a prompted recall format [**2015 Smartphone, 3**]. The processing algorithms that are typically used by these apps also has the potential to minimize the need for respondents to manually input information, potentially reducing response burden [**2015 Smartphone, 3**]. The periodic tracking of the location of the device also allows context-specific questions to be posed to survey participants in real time [**2016 Smartphone Technical I, 3**].

From the perspective of the survey administrator, there are a number of benefits when using a smartphone app to conduct a travel survey. One of the more attractive aspects stems from the increasing levels of smartphone ownership that have been seen in recent years. Smartphone ownership has been on the rise across all age groups [**2015 Smartphone, 7.2**], and the percentage of households with at least one cellphone has also been increasing [**2015 Smartphone, 1.0**]. Smartphone surveys are easily scalable, have low marginal costs, and allow for progress and survey responses to be tracked [**2015 Smartphone, 7.2**]. Due to the relatively low response burden and marginal costs, this mode can also be used to collect data over multiple days [**2015 Smartphone, 7.1**]. Furthermore, the ability to supplement data from GPS sensors with that from other sensors, such as GSM, the accelerometer, and Wi-Fi, help to improve data quality [**TAC P2, 4.3**].

Disadvantages: One of the main issues associated with the use of smartphone apps to conduct a travel survey is the need to validate information. The inference of trip information from raw data requires data that is both comprehensive and accurate. Due to issues such as cold starts and the urban canyon effect, this is often not the case [**2015 Smartphone, 3.1**]. As a result, participants are often asked to validate the inferred trip information [**2015 Smartphone, 3**]. The effect that data collection can have on the battery life of the device is also a major consideration. Oftentimes, there is a delicate balance between the frequency and accuracy with which data are collected and battery drain [**2015 Smartphone, 3.1**]. Survey apps that have a considerably detrimental impact on battery life are more likely to be uninstalled, which can introduce bias into the survey results.

From an administrative standpoint, smartphone applications come with several challenges. First, forming or obtaining a sample frame of cellphone numbers can be a costly proposition. Second, the results obtained through this type of survey tend to do a poor job of representing the target population, as younger members of the population may be over-represented [**2015 Smartphone, 7.2**]. In addition, individuals with lower levels of education and lower incomes have both shown a greater unwillingness to participate in smartphone surveys [**2016 Smartphone Technical I, 3**]. Compared to the respondents of the 2016 TTS, the users of the *City Logger* smartphone app had a higher proportion of respondents who were younger, male, and employed full-time [**2017 Smartphone Field, 4.1**]. Among the users of the *City Logger* app, the participants who were recruited through crowdsourcing were more likely to be students and less likely to be employed full-time [**2017 Smartphone Field, 4.1**]. Third, the design of the user interface can have a significant impact on the results of the survey, as discussed in [**Final, 6.1.4**]. Finally, the tracking of individuals creates a whole host of privacy concerns due to the nature of the data collected through smartphone apps [**2015 Smartphone, 8.1**].

5.3.2 Design Considerations

Aside from the approach taken to validating data, the key design decision that must be made when conducting a smartphone-based travel survey is the trade-off between the frequency and accuracy of data collection and battery drainage. Battery drainage is one of the key limitations of using smartphone apps to log locations, and as a result, the feasibility of using the device's other sensors (e.g. GSM, Wi-Fi) has been investigated [**2016 Smartphone Technical I, 3**]. In some cases, data collected by the GSM and Wi-Fi sensors are used in lieu of the GPS sensor in order to limit battery drainage [**2015 Smartphone, 5**]. Reducing the frequency of data collection is another method of addressing the battery drain issue; however, this increases the risk of missing short trips and reduces the number of points available for link matching [**2016 Smartphone Technical I, 3**]. Examples of the approaches taken to mitigate battery drainage issues include:

- Defining geofences, whose boundaries must be crossed before the location of the device is logged
- Using the accelerometer, gyroscope, and magnetometers that are built into the device to log velocity and acceleration information when the GPS signal is lost to facilitate the use of dead reckoning to estimate the present location of the device

For more detail on the approaches used to reduce the impact that a smartphone app has on battery drainage, see [**2015 Smartphone, 5**].

Another significant concern is the privacy of the survey participants. Past studies that looked at privacy in smartphone surveys have found that clear and simple communication can increase response rates [**2015 Smartphone, 8.1**]. Bouwman et al (2013) suggest a number of approaches to address privacy concerns, such as:

- Storing information using a password-protected login.
- Not collecting personally identifiable information.
- Only allowing researchers associated with the project to access disaggregate information.
- Ensuring that disaggregate information not be publicly accessible.
- Ensuring that the data be collected and analyzed by different entities.

In addition, privacy policies should be documented, and a user-agreement and privacy-related FAQ should be created [**2015 Smartphone, 8.1**]. Because precise location and travel data are being collected, the explicit consent of survey participants must be obtained [**2016 Smartphone Technical I, 3**].

5.3.3 Processing and Usage of Data

Part of the potential for smartphone surveys to reduce response burden stems from the fact that respondents are asked to validate the trip characteristics that are inferred from raw data. The trip characteristics that are typically inferred include: trip ends, trip legs, travel mode, and activity or trip purpose. The ability to accurately identify locations and trip ends is often impaired by a reduction of the effectiveness of GPS sensors indoors and cold starts, where the location of a device is not logged at the outset of the trip. Cold starts can lead to gaps in data at the beginning of trips. This may require assumptions to be made about where a trip starts and ends. The quality of the data collected via smartphone app can also be affected by battery life considerations, to the extent that data may be recorded less frequently or in a less accurate manner in order to reduce battery drain. In an attempt to address this issue, some apps use GSM and Wi-Fi networks to address gaps in the spatial information collected through GPS, while others have relied on accelerometer readings to activate the GPS sensor [**2015 Smartphone, 3**]. When it comes to identifying trip ends, two general approaches have been taken – identifying clusters of points and identifying locations where the loss of signal is related to participation in an activity. In the former approach, the identification of trip ends tends to be done based on a set threshold of time where no movement takes place. In other cases, a horizontal accuracy threshold is combined with location data to determine whether a person is "stationary" [**2016 Smartphone Technical I, 3.5**].

When it comes to inferring the mode of travel, spatial information on its own tends to be inadequate. When this information is collected via smartphone, accelerometer data tends to be used in conjunction with spatiotemporal data to detect modes. In practice, the approaches used to infer travel modes include the use of: rule-based algorithms, fuzzy logic, post-processing machine learning algorithms, and real-time sensor processing [**2016 Smartphone Technical I, 3.5**]. The accuracy of mode detection algorithms can be improved through a greater level of aggregation of modes (e.g. transit instead of bus, subway, and streetcar), greater distinctions between modes, and the incorporation of GIS and GTFS data [**2016 Smartphone Technical I, 3.5**]. At this point in time, it appears that a combination of the rule-based and machine learning approaches is likely to yield the most accurate results. Regardless of the information that are used to infer the mode of travel, the processing algorithm should include a feedback mechanism (such as machine learning) in order to improve the accuracy of the predictions.

Inferring activities and trip purposes is the one of the most challenging aspects of conducting a smartphone-based travel survey. The inference of this information typically requires more validation than inferences of either mode or location. Attempts to infer trip purpose through passive means have included the use of land use data, third-party data, and open-source data (e.g. FourSquare, Google API). Some studies have also attempted to apply rule-based heuristics to infer activity types. In some cases, some studies have attempted to incorporate information from Wi-Fi networks or socio-demographic information (e.g. age, gender, education level, distance to work, etc.) to infer activities [**2015 Smartphone, 3**]. Inferring trip purpose tends to be easier to do in suburban areas that in urban ones, and point-of-interest data can be used to assign probabilities based on the density of nearby locations [**2016 Smartphone Technical I, 3.5**].

5.3.4 Experience from Other Surveys

Within Canada, smartphone-based travel surveys have been used to estimate indicators of travel, household time-use diaries, and to compare the results obtained through web-based prompted recall and

GPS studies [**TAC P2, 4.3**]. In Singapore, data collected through the Future Mobility Survey (FMS) was used to study validation, battery optimization, and the potential to use smartphone surveys to collect data over multiple days. Other studies that have investigated the use of smartphones to conduct travel surveys have looked at:

- The accuracy of passively recorded trip information.
- The impacts of the app on battery life.
- Methods to improve response rates.
- Guidelines for creating user-friendly apps.
- Instrument biases.
- Methods for recruitment.
- The impacts of privacy concerns.

Studies such as Zhao et al., 2015 have looked specifically at the accuracy of stop, mode, and activity detection. A full review can be found in [**2015 Smartphone, 2**].

5.3.5 Selecting a Smartphone App:

The growing prevalence of smartphone-based surveys means that a number of location logging applications are available for download and use from sources such as the Google Play store or the App Store. Given the number of options that are currently on the market, selecting which application to use can be a daunting task. The difficulty of this task is compounded by the fact that an independent comparison of the performance of apps and processing suites with respect to a rigorously defined ground truth has not been undertaken [**2016 Smartphone Technical I, 1**]. The ad-hoc nature of location tracking and trace processing within smartphone apps, in addition to the context-specific nature of the outputs of these apps make it difficult to objectively compare apps or processing suites [**2016 Smartphone Technical I, 4**]. In order to address this issue, a field test was undertaken in the summer of 2016, wherein the link, leg, and trip information collected using various smartphone applications was compared against a "properly recorded" ground truth. The goals of this field test were to:

- Better understand what uses to which smartphones can and cannot be applied.
- Understand the data collection possibilities that can be enabled by using smartphones.
- Develop expectations of the accuracy of the information collected in different scenarios.
- Identify and describe best practices as they relate to app design.

Full detail is available in [**2016 Smartphone Technical I**]. Based on the lessons learned from this assessment, the study members present a number of recommendations that pertain to the selection of a smartphone app. These recommendations include [**2016 Smartphone Technical II, 5**]:

- Selecting an application based on its ability to correctly identify the modes that are most frequently used in the study area.
- Conducting both internal pilots and pre-tests before signing a contract with an app developer.
- Requiring that an app that works on both the Android and iOS operating systems.
- Requiring that an app be able to run in the background and collect data in a passive manner, without excessively draining the battery.
- Requiring that an app be able to collect additional information on any trip that is inferred.

At minimum, any app that is used to conduct a travel survey should:

- Be able to log information passively.
- Be able to record traces and detect trips and/ or trip legs.

- Include a simple installation procedure that does not require the use of a token or a multi-platform account creation process.
- Allow for a branching structure to be incorporated into the questionnaire.
- Feature a user-friendly interface and upload trips automatically via Wi-Fi.
- Include a simple-to-use validation process, either through real-time prompts or a travel diary.
- Be able to invite other household members and link household-level data.
- Feature common branding across the Android and iOS platforms.
- Include a public-facing website and FAQ page.
- Ensure compatibility with major smartphones.

5.3.6 Recommendations

Smartphone-based travel surveys are appropriate when precise spatio-temporal information is desired, or when route or facility choices are being studied. Due to the low marginal costs and response burden, this mode is also suited to applications where data will be collected over multiple days. In addition, smartphone surveys are well-suited to studies of persons who display high rates of cellphone usage.

However, there remain some key issues that need to be resolved before smartphones can be used as part of a core survey; in the mean-time, they are best suited for linked or independent satellite surveys. In the near term, methods to fuse smartphone survey data with CATI or web survey data requires further investigation. In addition, methods to reduce battery drainage must be developed further. Improvements are also needed in algorithms used to infer travel information (particularly trip purpose and mode). Issues also remain to normalize or account for survey mode biases among smartphone, CATI, and web surveys, both in recruitment and execution.

5.4 In-Person Surveys (CAPI)

Although in-person surveys may be regarded as a thing of the past, they are far from antiquated. Once considered the default mode for collecting data, their dominance was eroded by decreases in the marginal costs of other survey modes [**2017 In-Person Field, 2.0**]. This survey mode has evolved and adapted to make use of newer technologies, with the current iteration of in-person surveys taking the form of computer-assisted personal interviews (CAPI). This form of data collection is still common in Europe and Australia and developing country contexts, with the most attractive aspect of this mode being the ability of an interviewer to administer a fairly complex survey instrument. While the costs of using this mode remain an issue, there are a few applications in which this mode is still cost-effective [**2017 In-Person Field, 2.0**].

Advantages: In-person surveys have generally achieved one of the highest response rates and levels of data quality relative to other survey methods [**TAC P2, 2.3.2**]. Although cost has been the main driver in the declining use of in-person interviews to collect data, these costs partly arise from one of the advantages to using this mode – the potential to collect detailed data. Face-to-face collection of data tends to mitigate issues of trip under-reporting, meaning that a greater share of travel is reported. This may stem from the ability of interviewers to record more complex trip chains or the ability to provide clarifications. The presence of an interviewer, particularly in the homes of respondents, creates the potential to conduct long and detailed interviews and the potential to probe respondents for more detailed or additional information. Furthermore, the utilization of interviewers allows for the administration of both visual and verbal cues and facilitates real-time quality assurance. In addition to the potential for improved data quality, the in-person approach may be the most effective means of getting respondents to participate in the survey. This could be attributed to the role that the interviewer plays in reducing the importance of technical literacy, the potential for interviewers to gain the trust of respondents by building a rapport, or the ability to incorporate a self-administered portion component of the survey to help assuage privacy concerns (although the presence of the interviewer still creates the potential for social desirability bias). [**2017 In-Person Field, 2.0**]

Disadvantages: The relatively high response rates and levels of data quality come at the cost of higher per-completion costs, which are the highest among the various survey modes (Sharp & Murakami, 2005). This issue has limited the use of face-to-face interviews to highly specialized, small-sample, complex surveys. The relatively high costs of this survey mode primarily stem from the labour-intensive nature of the data collection process. Multiple attempts may be required to contact respondents [**2017 In-Person Field, 2.0**] and multiple visits to a residence may be necessary to complete the data collection process [**2017 In-Person Field, 2.2**]. As a result, fieldwork may take longer than cases where CATI methods are applied. Broadly speaking, the resource efficiency of in-person methods is fairly dependent on the conditions of the survey area. These methods typically require trained interviewers who live in fairly close proximity to the sample, although the need to address travel and logistical requirements remains [**2017 In-Person Field, 2.0**]. Additionally, this survey mode is the most vulnerable to disruptions and issues stemming from crime [**2017 In-Person Field, 2.0**]. Due to the role that the built environment plays in the cost-efficiency of this survey mode, geography often factors into the sampling process. As a result, geographic stratification is often seen [**2017 In-Person Field, 3.2**].

TTS 2.0 Field Test: A field test was undertaken as part of the TTS 2.0 project to study the conditions under which in-person surveys can be utilized within the context of a household travel survey **[2017 In-Person Field].** In order to study the "cost-effectiveness and data quality implications" of incorporating in-person interviews into the conduct of the TTS, interviewers were sent to households in seven census tracts in Toronto. These tracts were chosen based on [**2017 In-Person Field, 3.2**]:

- Their poor representation of persons aged 18-34 in the 2011 TTS,
- Their proximity to subway stations or easy transit accessibility,
- Their relatively high proportions of "low-density residential" address points, and
- The congruence of their boundaries with those of traffic analysis zones.

Sampled households were sent an advance notice to inform residents that interviewers would be coming to collect travel information [**2017 In-Person Field, 1.0**]. Interviewers were given tablet computers with internet access and visited a specific set of households each day – in the event that the residents were either not available or not home, the interviewer's households with a unique survey code to allow the survey to be completed at their leisure [**2017 In-Person Field, 1.0**]. After comparing the data obtained from the in-person interviews ("2017 CAPI"), 2011 census, 2016 census, and 2011 TTS, there were a number of areas in which the CAPI out-performed the TTS data. Specifically:

- The mean age of respondents in the CAPI survey was closer to the 2011 census value than was the 2011 TTS [**2017 In-person Field, 5.3].**
- The representation of persons aged 20 to 39 in the CAPI dataset more closely resembled the census [**2017 In-person Field, 5.3].**
- There was a higher share of large households and vehicle ownership, although this may be due to the desire to select census tracts with higher shares of single-family housing [**2017 In-person Field, 5.3].**
- Higher income categories were more likely to be reported [**2017 In-person Field, 5.3].**
- There was a greater number of walking trips reported in the CAPI survey, which was attributed to the probing of interviewers for these trips [**2017 In-person Field, 5.4**].

These findings show that in-person surveys are useful in certain contexts and may have a place in the conduct of an HTS.

Selection and Use: When selecting sampling units from a sample frame for a CAPI survey, homes that are currently under construction, unoccupied homes, residences where no one speaks English, and homes being used as short-term rentals can create issues when it comes time to send interviewers into the field [**2017 In-person Field, 8.2.3**]. The need to return to a home multiple times, e.g. because the residents not being home when an interviewer arrives, can also significantly impact costs. In practice this issue has been addressed by sending an advanced notice that the survey will be taking place, and through the creation of written survey invitations that provide recipients with a link to the corresponding web survey. In the field test of the in-person survey method that was conducted in 2017, the completion rate of the mailer survey was roughly one-tenth that of the CAPI survey (5% vs. 50%) [**2017 In-person Field, 5.2**]. Many of the respondents to the survey conducted during this field test told their interviewer that they had received and read the initial letter and would not have participated in the survey without it.

While cost is likely to remain a fairly significant consideration in the choice of mode, there are applications in which in-person surveys can be both useful and cost-effective. The use of CAPI surveys is feasible for intercepts surveys, as well as situations where data collection efforts for which the target population is small, or the survey area is accessible and walkable. The use of CAPI surveys should also be considered in situations where:

- Information on complex behaviours is sought [**2017 In-person Field, 1.0**],
- Landline penetration rates are low [**2017 In-person Field, 1.0**], or
- Household travel survey data is being supplemented for areas where the urban form and dwelling type composition make it economically feasible [**2017 In-person Field, 6.0**].

Moving forward, the features and aspects of CAPI surveys that make them capable of collecting data on complex behaviours should be studied, so that the lessons can be applied to the design of web and smartphone surveys. Additionally, inverted sampling procedures should be further investigated and developed to facilitate the in-person administration of surveys in those contexts.

5.5 Multi-Modal Surveys

As the preceding sections have shown, a single survey mode cannot be expected to be sufficient for large-scale travel surveys. While efforts to expand and develop the capabilities of the various survey modes that currently exist must continue, survey design in the near term should take a multi-modal approach to data collection into consideration. The idea of conducting a travel survey using more than one mode was originally seen as a means of addressing the declining rates of participation in CATI surveys. The goal was to improve the representation of certain demographic in the survey dataset [**2016 Sample Frame, 6.0**]. The conduct of travel surveys in this manner has become more prevalent, with prospective respondents typically being offered the choice of participating in a survey online or over the phone.

As with any approach to data collection, there are inherent benefits and issues to a multi-mode approach. The decision to conduct a survey using multiple modes typically requires the careful consideration of coverage, non-response, and measurement errors [**2016 Sample Frame, 6.0**]. The greatest benefit of conducting a multi-modal survey is the potential improve response rates and to reduce non-response bias; however, this comes at the cost of having a data set that is a combination of smaller datasets, each of which has its own inherent biases [**2016 Sample Frame, 6.0**]. For more information on the factors that must be considered when conducting a multi-modal survey, see [**2016 Sample Frame, 6.0**]. In practice, the addition of a new survey mode has produced mixed results when considering improvements to response rates, reducing non-response bias, and providing better trip estimates. Specifically, the inclusion of an additional mode is not guaranteed to improve demographic representation to a significant extent, and the introduction of an additional sample frame has the potential to introduce different non-response biases [**2016 Sample Frame, 6.0**].

In spite of these issues, it is recommended that a multi-modal approach be taken to conduct large-scale travel surveys. This approach should also be used for surveys that target populations in which different subsets have preferences for different modes. Moving forward, it is crucial that methods to harmonize the biases inherent to each survey mode and sample frame be investigated and developed. All methods of measurement will have their flaws, but the ability to create an amalgamated dataset that contains a consistent set of flaws can provide end-users of travel demand data with a certain degree of certainty. Additionally, a comprehensive ontology or dictionary of terms such as mode, trip or activity should be developed to ensure that terms are used in a consistent manner across surveys.

6 DESIGNING TO MINIMIZE BIASES

The validity of inferences can be derived from survey data is heavily affected by the presence of bias during collection. Surveys must be carefully constructed to ensure that a representative sample, one that adequately characterizes the distribution of population attributes and behaviours, is drawn. The representativeness of the sample is a critical factor that determines whether statistically valid inferences can be drawn regarding the attributes and behaviours of the population. Amongst potential survey biases, the most obvious threat to the validity of survey results is non-response bias, which can result from the respondents choosing not to answer specific questions or to refuse to participate in the survey. Survey response rates should be maximized as higher response rates tend to reduce the likelihood that the survey data will contain major biases. The keys to preventing low response rates include the minimization of respondent burden (i.e. respondent fatigue bias) and the maximization of a respondent's motivation to participate in the survey (i.e. non-response bias).

Aside from these biases, there are many other biases that can affect the quality of the survey data. Two of the more crucial biases are survey mode bias, which has become a critical concern in travel surveys where multiple survey modes are used, and proxy bias, which has long been a concern for HTS. Given the current state of practice, it is crucial that biases be limited and managed when a survey is being designed, as it is currently not possible to correct or harmonize the effects of these biases. The goal of this chapter is to identify the effects of key biases pertinent to household travels surveys, and to provide proactive approaches to minimize their impacts. Categories of biases discussed are survey-mode, respondent-fatigue, non-response and proxy.

6.1 Survey Mode Bias

Survey mode bias has become increasingly problematic in recent years, largely due to the tendency of large-scale travel surveys to be conducted using multiple modes. Simply put, survey mode bias stems from the manner in which respondents experience the survey. The mode through which a survey is administered can affect how respondents answer questions, partly due to the expectations that respondents have when progressing through the survey. The objective of this section is to identify and summarize the effects of the biases associated with the use of various survey modes, and to provide best practices for designing a survey that uses each mode. Four survey modes will be examined: computer-assisted telephone interview (CATI), computer-assisted in-person interview (CAPI), computer-assisted web interview (CAWI), and smartphone surveys. For more information on these modes, see **Final, 5**].

6.1.1 Computer-Assisted Telephone Interview (CATI)

One issue with the use of the CATI mode is the inability to get a complete picture of the trips made by respondents. When completing survey over the phone, respondents tend to omit 20-30% of their trips [**2015 Web, 3.2.4**]. This coupled with the tendency for respondents to be unable to provide precise information on their travel times, the places they visited, or the routes that they took, can lead to survey data that do not adequately reflect the travel of a given respondent [**2015 Web, 3.2.4**]. The issue of under-reporting is most pressing when it comes to travel using active modes (i.e. walking and cycling), as information on these trips is more likely to be omitted or be inaccurate [**2015 Landline, 3.0**]. In order to address this issue, it is recommended that:

- Interviewers be instructed to emphasize the importance of the data in order to help motivate respondents to provide more information
- Ensure that interviewers prompt respondent to provide information on their non-motorized trips

The presence of an interviewer can also affect how respondents answer questions. In addition to their potential to induce social desirability bias, discussed in [**Final, 5.1**], survey data can also be affected by variations in how different interviewers conduct the survey. This issue may arise when some interviewers prompt respondents for additional information while others do not. The initial learning curve experienced by interviewers may also introduce bias into the dataset. In order to address this issue, interviewers should be adequately trained and instructed to stick to their script.

Combating non-response is a critical consideration in the design of any survey. One method of reducing non-response in CATI surveys is to repeatedly attempt to call households at later date until contact is successfully made or a maximum number of attempts is reached [**TAC P2, 2.4.2**]. Another method that has been used to address non-response is the mailing of a survey invitation to sampled households prior to the CATI interview. These invitations often explain the objectives and significance of the survey, in addition to specifying the target interview date [**TAC P2, 2.4.2**]. This method has been shown to increase response rates, particularly among the residents of single-family housing units [**TAC P2, 2.4.2**]. The use of mail as the initial contact method has also been found to be the most promising approach taken in mixed-mode surveys [**2016 Sample Frame, 6.0**]. The potential for proxy bias is also prevalent in CATI surveys, although it is a necessary evil when it comes to household travel surveys. Methods to minimize proxy bias are discussed in [**Final, 6.4**].

6.1.2 Computer-Assisted in Person Interviews (CAPI)

Similar to CATI surveys, CAPI surveys are also susceptible to interviewer bias. In the case of CAPI surveys, interviewers are often offered an incentive that is tied to the number of completed survey responses that they can obtain. This incentive structure can create the potential for opportunistic behaviour on the part of the surveyors, such as the falsification or rushing of interviews, in order to increase their number of completed surveys [**2017 In-person Field, 8.2.5**]. Unlike CATI surveys, quality assurance can neither be conducted through the monitoring of the conduct of the interviewers, nor by observing their interactions with respondents [**2017 In-person Field, 8.2.5**]. Of course, the presence of an interviewer also makes it more difficult to obtain sensitive information or information on socially undesirable behaviours [**2017 In-person Field, 2**]. Interviewer bias in CAPI surveys can be addressed by instructing interviewers to stick to the script that is given to them, and by providing them with adequate training. Additional work needs to be done to investigate potential approaches to conducting quality assurance checks, as monitoring conversations with respondents raises both legal and ethical concerns.

6.1.3 Computer-Assisted Web Interviews (CAWI)

CAWI surveys, and web surveys in general, are an example of a survey mode whose design can have a significant impact on if and how a respondent answers the questionnaire. Discussed in detail in [**2015 Web, 3.2.4**], at the root of this issue is the tendency for people to apply visual heuristics when they are presented with a web page filled with information. As a result, the manner in which response options are presented may affect how the respondent answers the question. Because of this issue, a number of standard user interface and survey design practices have been developed, which include:

- Scaled response options should be evenly spaced (an uneven spacing may result in the option closest to the visual midpoint being chosen more often)
- All response options should be visible upon first glance (people tend to employ a satisficing approach to completing a web survey and may not change their response if a better option is revealed later)
- Avoid the use of jargon

For more detailed design recommendations, refer to Sections 2, 3, and 4 of [**2016 Web Design**].

The potential for the design of a web survey to affect how a respondent experiences a survey can partially be attributed to two factors: usability issues and variability in the technical aptitudes of the respondents. Usability issues, and any resulting frustration, are the two most common causes of early survey termination [**2015 Web, 2.2**]. The use of a web survey may also place an additional burden on respondents who are distrustful of the web [**2015 Web, 2.2**]. Although there is not a consensus on the extent to which burden affects response rates, increases to burden are generally detrimental to response rates. Web surveys that are not designed to accommodate a wide range of technical aptitudes may increase the burden experienced by respondents with lesser technical aptitudes when they attempt to complete a web survey [**2015 Web, 2.2**]. Additionally, failing to design a survey to accommodate people with varying degrees of technical aptitudes can increase the number of observations in the final dataset that include measurement errors [**2015 Web, 3.2.4**]. From the data obtained during the field test of *TRAISI* that was conducted in 2017, it was found that older respondents are the ones who typically experience more difficulty and respondent burden when completing web surveys [**2017 Web Field Test, 4.2.4 and 4.3.1**]. This was exemplified in the time that it took a respondent to complete the trip diary, which increases significantly as the age of the respondent increases [**2017 Web Field Test, 4.2.4 and 4.3.1**]. In order to address issues stemming from usability and a lack technical aptitude, it is recommended that:

- Web accessibility guidelines for accommodating the diverse needs of respondents, particularly those with disabilities, are followed [**2016 Web Design, 2.7**];
- Respondents are provided with the option to transfer to another survey mode, such as CATI, without losing their progress;
- Respondents are provided with resources to help them complete the survey, such as video tutorials that are embedded into the survey, short and simple instructions to help guide them through the survey [**2017 Web Field, 3.3.6**], or the opportunity to call or contact an interviewer for help; and
- The survey be pilot tested and be subjected to usability tests prior to its conduct, in order to facilitate the iterative improvement of its usability [**2017 Web Field, 3.3.1**]

The most detrimental consequence of frustration and response burden is the abandonment of the survey. A key factor that distinguishes CAWI surveys from CAPI and CATI surveys is the absence of an interviewer. The absence of someone who can encourage respondents to complete the survey is one reason why CAWI surveys tend to experience higher drop-off rates. Oftentimes, drop-offs tend to occur at the trip diary stage of the survey. The impact of not having an interviewer is two-fold: the respondent must learn how to report a relatively complex set of information instead of having someone record it on their behalf, and do not have someone encouraging them to complete the survey. The difficulty associated with designing a web interface that collects the detailed information required of a trip diary can also compound this issue. This trend of respondents dropping out of the survey at the trip diary stage was seen in both the 2017 *TRAISI* field test and 2016 TTS; 59% of respondents who dropped off did so at the trip diary collection stage of the TTS [**2017 Web Field, 5.1**]. To minimize and mitigate the effects of survey mode bias in CAWI surveys, it is recommended that:

- Significant care and attention be given to the design of the trip diary question interface, including extensive usability testing [**2017 Web Field, 3.3**]
- If possible, make follow-up phone calls to respondents who dropped out of the web survey to verify the information in the trip diary [**2017 Web Field, 5.1**]
- Respondents are provided with the opportunity to switch survey modes without losing the information that they have already entered
- A live help/ technical support feature be incorporated into the web survey interface

During the 2016 TTS, interviewers made up to five telephone calls to households who had abandoned their surveys to provide technical assistance (R.A. Malatest and Associates Ltd., 2018). Using this strategy, 5,488 previously abandoned web surveys were completed over the phone (R.A. Malatest and Associates Ltd., 2018). This result highlights the importance of providing respondents with the opportunity to complete their survey using a different mode.

6.1.4 Smartphone

Many of the biases inherent to the use of smartphone-based surveys can be attributed to the design of the application and the user interface. Although web-based surveys are the mode most closely related to smartphone questionnaires, the impact that design can have on responses varies between the two. For example, compared to respondents who participated in the survey over the web, mobile users tend to take longer to complete the questionnaire, may perceive that the survey is longer, and tend to abandon the survey at a higher rate [**2015 Smartphone, 4.3**]. In addition, responses to open-ended questions tend to be consistently and significantly shorter in length when provided using a smartphone than when the survey is completed using a computer (Wells, et al., 2014). In a joint field test of the *City Logger* app and *TRAISI* web survey interface, demographic differences between respondents were observed. Smartphone app respondents reported higher household incomes, though these respondents also declined to answer the household income question at a higher rate [**2017 Smartphone Field, 4.3**]. Smartphone app respondents also tended to be younger and more likely to be female compared to the web survey respondents [**2017 Smartphone Field, 4.3**]. To a certain extent, issues stemming from survey design can be mitigated by using well-designed, mobile-optimized surveys to collect data [**2016 Smartphone Technical I, 3.5**]. Other methods to reduce the impact of user interface on survey data include:

- Ensuring that the app is designed in a streamlined manner to mitigate space constraints [**2015 Smartphone, 3.5**]
- Including in-app tutorials [**2015 Smartphone, 4.2**]
- Presenting a walkthrough each time that the user accesses a new section of the survey, rather than presenting a comprehensive walkthrough when the app is first launched [**2015 Smartphone, 5**]
- Limiting the use of maps to visual aids, rather than interactive interfaces, as the space restrictions may make interactions (e.g. pinching, zooming tapping) difficult [**2015 Smartphone, 5**]
- Replacing open-ended questions with closed-ended ones, where possible, to reduce respondent fatigue and bias [**2015 Smartphone, 4**]
- Having respondents complete the pre-survey questionnaire right after they create their accounts, to reduce drop-out rates and ensure that trips can be associated with the household and personal characteristics of the users [**2017 Smartphone Field, 5.2**]

A critical consideration in the design of a smartphone survey is how and when respondents will be asked to validate the information inferred by the built-in processing algorithms. While the inference of trip ends, mode, and trip purpose can help to reduce the burden experienced by the user, survey respondents must still be relied upon to validate the inferred information [**2015 Smartphone, 3**]. It is recommended that validation be approach one of two ways [**2016 Smartphone Technical II, 5**]:

- *Real-time prompting* with the possibility to enter information after the fact and the ability to edit responses that have already been submitted
- *Retrospective input* with the possibility to edit responses

The use of real-time prompts has the potential to increase the certainty that the information will be correctly recalled, although they may be bothersome for some respondents [**2016 Smartphone Technical II, 5**]. In the event that real-time prompting is used, notifications for prior trips should disappear when a new movement episode is detected – this can help to reduce the likelihood of inaccurate information being collected [**2016 Smartphone Technical II, 5**]. If respondents will be asked a large number of questions after each activity episode, a retrospective approach be more suitable than real-time prompting [**2016**

Smartphone Technical II, 5]. Delivering prompts through the app can reduce the likelihood that memory loss will affect the quality of the data collected, and visual cues can be generated on-the-fly to help jog the memory of respondents [**2016 Smartphone Technical I, 2**]. The amount of time that users will be expected to participate in the survey should be take into consideration when deciding on the level of prompting and number of questions that respondents will be asked. These two approaches were studied in a field test of the travel survey smartphone app *City Logger*, described in [**2017 Smartphone Field**]. Overall, both approaches were found to yield data of an acceptable quality. The travel diary approach to validation was found to provide a higher validation rate, while the real-time prompt approach resulted in a greater number of validated days [**2017 Smartphone Field, 5.1**]. The benefit of the real-time prompt approach is that the error associated with using this approach can be reduced for users with multiple days' worth of data, by applying post-processing algorithms to infer missing information [**2017 Smartphone Field, 5.1**]. Overall, it is recommended that a survey app allow for a mix of real-time and retrospective input and edits [**2017 Smartphone Field, 5.2**].

In addition to the design of the app, there are a number of other aspects of a travel survey smartphone app that can affect responses. Battery drainage can have a significant impact on responses. Respondents who experience significant battery drain due to the smartphone app may uninstall the app or terminate their participation in the survey out of frustration. A significant drainage of battery power can also result in the device entering power saver mode, which may cause incomplete information to be collected [**2015 Smartphone, 3.3**]. App loading times, cold starts, and the urban canyon effect are also key concerns [**2015 Smartphone, 3**]. It is recommended that the loading time of the app should be reduced to minimize fatigue and should ideally be kept below five to eight seconds (Nah, 2004), although some studies have found that people tend to wait longer if a progress bar is present [**2015 Smartphone, 5**]. Extensive pilot testing of the smartphone app should be undertaken to test for significant battery drainage issues. For guidelines on selecting a smartphone app, see [**2016 Smartphone Technical II, 6**].

6.2 Respondent Fatigue Bias

The influence that design can have on the response rate of a survey can primarily be attributed to its potential to fatigue respondents, leading to the introduction of respondent fatigue bias. Respondent fatigue bias occurs when a respondent's attention and motivation to complete the survey declines as they progress through the survey. This decline may cause respondents to provide false information, whether consciously or subconsciously, in order to answer a question or complete the survey faster. Increases in respondent fatigue can be detrimental to data quality and can lead to respondents prematurely ending their participation. The goal of this section is to provide a set of best practices for survey design and execution which aim to reduce response burden.

Web- and smartphone-based surveys are particularly susceptible to response fatigue bias due to the fact that respondents must learn how to progress through the survey on their own. The absence of a trained interviewer to help walk respondents through the survey interface creates the potential for the user interface of these types of surveys to have a significant impact on respondent fatigue. Various studies have shown that the user interface of a web survey can significantly sway respondents' attitudes towards the survey. A poorly designed user interface can be confusing and inefficient, and can evoke negative emotions for respondents, which in turn can compromise response rates and the quality of the data that are collected. In order to mitigate the negative impacts of the design of a user interface, standard UI and survey question design practices should be followed. These include:

- Designing the interface to conform to the natural behaviours that are exhibited by web users when navigating through websites and web surveys – a critical component of ensuring that the design is user-friendly [**2016 Web Design, 2.1, 2.2, 2.3**];

- Being careful in the use of colour, images, and typography to avoid influencing survey responses and to create a user-friendly interface [**2016 Web Design, 2.4, 2.5, 2.6**];
- Ensuring that the website adheres to the web content accessibility guidelines outlined by the Government of Ontario [**2016 Web Design, 2.7**]; and
- Carefully selecting the wording, structure, and design of questions to ensure that they are clear and comprehensive, and to avoid misinterpretations and unnecessary burden on respondents [**2016 Web Design, 3**]

For more detailed recommendation regarding UI design, refer to [**2016 Web Design**].

In addition to the design of the user interface, the decisions made regarding the questionnaire (particularly regarding its length), can affect fatigue. The length of a survey is positively correlated with respondent fatigue, although the magnitude of the correlation varies on a case-by-case basis. Setting respondents' expectations for the amount of time it will take to complete the survey is one approach that has been used to try and mitigate respondent fatigue. In practice, it is difficult to estimate how long a survey will take, because it is highly dependent on the size of the household. In the field test of in-person surveys, respondents who chose to participate in the survey through the web found the survey length estimates to be an annoyance [**2017 In-Person Field, 8.1.3**]. Particularly for a web survey, respondents may realize that they want to complete the survey at a different time or using a different device if they are provided with an estimated survey length, particularly if the length is significant [**2017 In-Person Field, 8.1.3**]. This realization may be to the detriment of survey completion rates, as the need to switch devices or remember to return to the survey is an additional burden [**2017 In-Person Field, 8.1.3**]. Other surveys have attempted to help respondents set their expectations for how long the survey will take by including progress bars to indicate their progress through the survey. In the literature, there have been conflicting conclusions regarding whether this approach motivates or deters respondents from completing surveys, though it is generally believed that progress indicators are more beneficial in short surveys [**2016 Web Design, 4.2**].

For a web survey, respondents who access the survey using a mobile phone may experience more fatigue than those who participate using a desktop computer. The perceived length of a survey tends to be greater for mobile respondents than their desktop counterparts (De Bruijne & Wijnant, 2013), which may be why completion times and survey abandonment rates tend to be higher among mobile respondents (Jue & Luck, 2014). This discrepancy highlights the need for responsive design and may indicate that less information should be collected through mobile surveys (compared to desktop surveys) in order to reduce the burden. The detrimental effects of fatigue were observed in the 2016 TTS. The administrator of this survey speculated that many cases of survey abandonment could be attributed to fatigue, due to the complaints that were received about the survey being cumbersome and too long (R.A. Malatest and Associates Ltd., 2018). Similar complaints were also received during the field test of the *TRAISI* web survey platform; respondents who were older or came from larger households tended to take longer to enter their trip information, and thus experienced greater fatigue and drop-out rates [**2017 Web Field, 5.1**].

Within the questionnaire, the trip diary is a major source of respondent fatigue. To a certain extent, this is to be expected, as it is one of the lengthiest and most detailed portions of the survey, and thus one of the most substantial sources of fatigue. The majority of the respondent drop-outs in the 2016 TTS and the various field tests conducted as part of the TTS 2.0 project occurred at the trip diary stage, seeming to confirm this expectation. In an attempt to address this issue, extensive usability testing of the *TRAISI* trip diary question was conducted; a summary of lessons learned and recommendations for designing a trip diary question for both desktop and mobile are provided in [**2017 Web Field, 3.3.6**]. As part of the usability testing, it was found that asking for additional route information neither significantly adds to the survey burden, nor does it decrease the trip rates reported by respondents. This finding comes with the caveat that respondents are twice as likely to report multi-modal trips when they are provided with a simplified version of the trip diary question as they are when asked to provide all of the details of their trips. Furthermore, the use of an API to provide suggested routes can help reduce fatigue, although adjusting and identifying the waypoints of a journey can prove to be a difficult task. Overall, collecting trip route information through a web survey is a viable option, although it is recommended that route information should not be collected for trips made on foot or by bike, so as to limit respondent frustration. Smartphones also provide a potential means of collecting high-quality information on the travel patterns of individuals, without burdening them by requiring that they recall and report every detail of their travel.

In addition to improving the usability of the survey interface and reducing the amount of information collected, the time needed to complete a trip diary question can be reduced by employing the announce-in-advance technique. This technique, wherein survey participants are told that they will be asked to recall the trips that they made on a specific day, has been found to reduce trip diary question response times [**2017 Web Field, 4.2.5**]. Compared to the prompted recall technique that is used in the TTS, the announce-in-advance technique has been shown to produce higher completion rates, reduce the time needed to complete the trip diary question, and improve data quality. Among the participants of the *TRAISI* field test, the announce-in-advance survey achieved a higher completion rate (76%) than the prompted recall survey (68%) [**2017 Web Field, 4.2.4**]. The respondents of the announce-in-advance survey also reported higher trip rates than the respondents of the prompted recall survey [**2017 Web Field, 4.2.5**]. Interestingly, the prompted recall technique achieved slightly higher response rates [**2017 Web Field, 4.2.5**]. The application of the ANOVA technique revealed that allowing proxy reporting reduces the response times for the trip diary portion of the questionnaire.

6.3 Non-Response Bias

The most impactful aspect in which the design of a survey affects the quality of the collected data stems from the role that design plays in the introduction of non-response bias. This bias arises when there are significant differences between the sampling units (e.g. households or individuals) who completed the survey and those who did not. The design of a survey can be the difference between the decision of a respondent to accept an invitation to complete the survey or to reject it. The rejection of the survey among the individuals or households that were included in the sample, regardless of whether they are unwilling or unable to participate, has the potential to introduce non-response bias into the survey results. Other factors, such as respondent fatigue, may also contribute to non-response bias. This section summarizes the issues pertaining to and the factors that influence non-response bias and presents strategies and approaches to reduce non-response bias.

The introduction and severity of non-response bias can be the result of numerous factors. First and foremost, the refusal of a prospective respondent to participate in a survey can result in non-response bias. It is important to note that non-response alone is not indicative of non-response bias, which stems from the existence of significant differences between travel behaviour of respondents and non-respondents. Naturally, the design of the survey will have an influence on non-response. For example, a web- or smartphone-based survey that is not designed to be compatible with the relatively small screens of mobile devices may be off-putting to respondents, which may increase non-response (and by extension, non-response bias) (Jue & Luck, 2014) [**2015 Smartphone, 4.1**]. Surveys that are left incomplete, due to factors such as respondent fatigue, can also contribute to non-response bias [**2017 Web Field, 4.3.1**]. The data collected through the field test of the *TRAISI* web survey software revealed that older respondents were more likely to drop out of the survey prematurely [**2017 Web Field, 4.3.1**]. It was also apparent that larger households had a greater propensity to drop out of the surveys; the average household sizes for complete and incomplete surveys were approximately 2.04 and 2.25 people, respectively [**2017 Web Field, 4.3.1**]. Based on comparisons between the datasets of the 2016 TTS and 2016 Canadian census, it appears that the data from the 2016 TTS exhibits non-response bias, specifically [**2017 Multiple Frames, 7**]:

- Households were more likely to be two-person households (37.7% TTS to 30.4% census) and less likely to have 5 or more people (7.2% to 11.1%)
- Persons below the age of 40 were underrepresented (40.6% to 49.7%), while those aged 40 and above were overrepresented

The relative lack of households with five or more members was attributed to the respondent fatigue associated with the completion of trip information for every member of the household.

The design of a survey is a double-edged sword – just as it can dissuade participation in a survey, so too can it be used to motivate respondents to participate in and complete a survey. First and foremost, it is important to ensure that the design of a survey is user-friendly to avoid drop-offs due to respondent fatigue. The survey interface should be polished, allow for effortless validation, and make it possible for respondents to exert some control over the amount of interaction that they wish to have with the app [**2015 Smartphone, 5**]. Respondents can also be motivated to continue to complete the survey by using a graphically pleasing design that provides respondents with feedback after every task [**2017 Web Field, 3.3.6**], or by incorporating features that provide a sense of achievement for ongoing participation [**2015 Smartphone, 5**].

The way that the survey is presented will also affect the motivation of respondents to complete the survey. The topic and the sponsor of a survey carry considerable weight in the decision of a respondent to participate in a survey [**2016 Web Design, 4.1**]. If a survey is sponsored by a government agency or an academic researcher, it should be indicated in the survey invitation or the introductory statement. These types of surveys tend to achieve higher response rates than those sponsored by commercial firms [**2016 Web Design, 4.1**]. When sending survey invitations by e-mail, subject lines that refer to prizes or offers should be avoided, as they tend to produce lower response rates than invitations that explicitly state that the e-mail is about a survey [**2016 Web Design, 4.1**]. Additionally, personalization should be avoided in invitation e-mails, unless the survey sponsor is of high status, such as a government agency or academic researcher [**2016 Web Design, 4.1**]. Personalization tends to be detrimental to a respondent's sense of anonymity, which may deter them from disclosing personal information in the survey [**2016 Web Design, 4.1**].

Another issue that may affect non-response bias is the decision of whether or not to require respondents to provide a response to a given question. On the one hand, requiring respondents to provide answer a question can help reduce instances where a survey observation contains missing data. On the other hand, requiring respondents to answer a question, particularly if it pertains to sensitive information, may motivate respondents to drop out of the survey. In the literature, there is a lack of a consensus on the impact of mandatory responses. For example, the results of Couper, Baker, and Mechling (2011) suggest that the impact of mandatory responses on break-off rates may be small. Conversely, Albaum et al. (2010) found that requiring responses significantly affects break-off rates, although it does increase the completeness of the data collected. Tourangeau et al. (2013) argued that the lack of significant correlation between mandatory responses and break-off rates are due to frequent use of mandatory responses in web survey, which has led respondents to grow accustomed to it. Surveyors must also be aware of ethical concerns that may arise when questions require responses.

The use of prompts could serve as a less coercive alternative to mandatory responses, particularly when data are collected through a smartphone app. When prompts are used, the decision must be made about how often respondents will be prompted for information in real time. The use of real-time prompts may be bothersome for some respondents, but it also produces greater certainty that the information will be correctly recalled [**2015 Smartphone, 5**]. It is recommended that a mix of real-time and retrospective input and edits be used. Users should be presented with a page within the app that allows them to see missed notifications, and to validate information in a traditional travel diary format. This would help to solve the issue of prompts not being seen and responded to in a timely manner, either because the timing was not ideal for the user or it was lost amongst other notifications.

When designing a survey, care must be taken to assuage the privacy concerns of potential respondents. In the 2016 TTS, some respondents abandoned the survey because they did not understand why the survey was soliciting demographic information that they deemed to be 'sensitive' (R.A. Malatest and Associates Ltd., 2018). Some of the participants of the field tests carried out as part of the TTS 2.0 project also questioned why certain questions were being asked and how the information would be used to support transportation planning [**2017 Web Field, 5.3**]. Providing respondents with a better understanding of the purpose of the questionnaire and its importance, particularly when sensitive information is being solicited, may help respondents sustain their motivation for completing the survey. Particularly when it comes to smartphone-based surveys, individuals from less educated backgrounds, as well as persons with lower incomes, tend to be less willing to participate [**2016 Smartphone Technical I, 3.3**]. This apprehension tends to stem from a mistrust of researchers and privacy concerns. A professional design can help convey a sense of security and legitimacy, although drawing attention to privacy issues can dissuade otherwise willing participants [**2016 Smartphone Technical I, 3.3**]. Asking questions that pertain to sensitive information, such as household income, can also dissuade respondents from completing the survey. In the 2016 TTS, many respondents complained about the pertinence of the household income questions, although interestingly, less than 1% of respondents left the survey at this stage. As has been done in many regional travel surveys, the questions pertaining to sensitive information were place towards the end of the survey. When the household income question was place at the beginning of the questionnaire used in the *TRAISI* field test, drop-offs were about 5% higher than when placed at the end of the survey.

Non-response can be combatted through the use of reminders. In the *TRAISI* field test that was conducted in fall of 2017, the use of reminders was shown to significantly increase response rates (15.5% in the summer field test compared with 28% in the fall) [**2017 Web Field, 4.3.1**]. The 2016 TTS had interviewers make up to five calls to households who had abandoned their surveys to provide technical assistance. This strategy resulted in the completion of 5,488 survey that would otherwise have been abandoned and had the potential to introduce or exacerbate the effects of non-response bias. This result shows the important role that offering CATI support can play in increasing completion rates (R.A. Malatest and Associates Ltd., 2018).

6.4 Proxy Bias

The decision to conduct a household-based travel survey carries with it the inherent issue of proxy bias. The decision to allow proxy reporting often stems from the cost and burden associated with attempting to contact and interview each individual in the household. The issue with this approach is that the trip information collected by travel surveys can be very specific and can significantly vary between respondents [**2016 Web Design, 4.5**]. Unfortunately, many household travel surveys have one member of the household report the trips made by the entire household. The use of proxy reporting can result in faster data collection, reduced operational costs, and the elimination of the need to conduct follow-up interviews with members of the household who were unavailable at the time of the initial interview [**2016 Web Design, 4.5**]. According to the U.S. Current Population Survey (CPS), the use of proxy reporting saves up to 17% of survey costs compared to surveys were all household members are interviewed (Cobb & Krosnick, 2009. On the other hand, it has been well-documented in the literature that number of trips reported by proxies are significantly lower than those of respondents who report their own travel (Hassounah, et al., 1993; Badoe & Steuart, 2002; Bose & Giesbrecht, 2004; Wargelin & Kostyniuk, 2014). The purpose of this section is to summarize the issues that arise from proxy reporting, and to recommend methods to reducing proxy bias.

The issues associated with proxy reporting have been well documented. At the forefront of these issues is the tendency for proxy respondents (i.e. persons who report information on behalf of someone else) to under-report the trips made by their fellow household members. While the exact extent to which trips are under-reported varies from context to context, it is a consistent trend in surveys that utilize proxy reporting. For example, based on the data collected through the field test of *TRAISI*, it was found that proxy respondents, on average, report 30% fewer trips compared to respondents who report on their own behalf [**2016 Web Design, 4.5**] [**2017 Web Field, 4.2.4**]. Studies have also found that home-based discretionary and non-home-based trips tend to be omitted by proxy respondents when reporting the travel of the other members of their household (Badoe & Steuart, 2002; Verreault & Morency, 2015). The under-reporting of trips has been found to be more common in the trip diaries of females than those of males, which has been attributed to the relatively higher frequency with which females make discretionary trips (Richardson, 2005; Wargelin & Kostyniuk, 2014).

At present, the most commonly used method for correcting proxy bias in travel surveys is the formulation and application of adjustment factors. The purpose of these factors is to adjust the trip rates provided by proxy respondents to match the rates of self-reported trips (Hassounah, et al., 1993; Stopher, et al., 2003; Verreault & Morency, 2015) [**2016 Web Design, 4.5**]. This approach can prove to be a difficult task, and the statistical validity of this approach has been called into question [**2016 Web Design, 4.5**]. Another popular method of countering proxy bias is the call-back, wherein interviewers will make additional calls to a household if respondents were not available during the initial call [**2015 Landline, 5**]. This method is applied in travel surveys conducted in Washington and New York, where proxy responses are only permitted for children aged 16 or younger; for adults, three call-backs are attempted before proxy reporting is permitted [**2015 Landline, 5**]. The most significant issue with this approach is that call-backs are costly and time consuming. Web surveys are now being regarded as a proactive means of reducing proxy bias.

Compared to CATI, web surveys provide greater flexibility, which allow surveys to be completed at the leisure of the respondents. As a result, it may not be as difficult to reduce proxy responses compared to CATI surveys. In the *TRAISI* field tests, approximately 27% of household members were proxy respondents – roughly half that of the CATI survey respondents in the 2016 TTS (52% of respondents). Based on the advantages that web surveys hold over CATI surveys, it should be possible to survey more than one member of a household without significantly increasing response burden. This approach of having multiple members of the same household was put to the test in a field test of the *TRAISI* web survey platform, described in [**2017 Web Field**]. As part of this test, respondents were given the choice between responding on behalf of another member of their household and having said member respond on their own behalf in a sub-survey. The ability of this method to minimize proxy bias was found to be marginal; the completion rate of the sub-survey was low, and it compromised the number of completed household surveys [**2016 Web Design, 4.2.5**]. As a result, the use of a household feature is to email out sub-surveys is not recommended.

Of course, the issue of proxy bias stems from the administration of travel surveys at the household level. With the rising prominence of web- and smartphone-based surveys, the practice of asking a single household member to report information on behalf of other household members should be re-examined. On the one hand, single-respondent surveys are much easier to administer, are generally cheaper, and typically have higher response rates than all-member surveys [**TAC P2, 2.3.2**]. On the other hand, single-respondent surveys have serious potential to generate significant proxy bias [**TAC P2, 2.3.2**]. If the single-respondent approach is used in a household-based survey, options for reducing proxy bias include:

- Having respondents prepare in advance for the interview by collecting the required travel data from the other household members
- Having all household members fill out a trip diary, with a single household member reporting the information in each diary to the survey interviewer
- Having each member of the household come to the phone in telephone interviews (though this poses issues related to interview scheduling)

The role of smartphone surveys within the framework of a household travel survey must also be examined, as they tend to be individual-based. The Dutch Mobility Survey offers an example of how the gap between individual- and household-based surveys might be bridged. In this survey, users are able to input supplementary information about their trips, including whether other household members accompanied them on said trip [**2015 Smartphone, 7.2**].

Household vs Individual Travel Surveys: While the combination of HTS and proxy reporting is still the dominant practice in North America, a trend towards individual travel surveys (ITS) can be seen in European travel surveys, such as those in France, Switzerland, and Spain (Armoogum et al., 2014). In an individual travel survey, a select number of individuals in the household are interviewed. The motivation to adopt ITS stems from [**TAC P2, 2.3.2**]:

- The relative ease with which single-respondent surveys can be administered and the tendency for these surveys to have higher response rates than so-called all-member surveys
- The reduced length and burden of ITS compared to HTS, in addition to the elimination of proxy reporting

HTS tend to be more difficult and expensive to coordinate, and they impose a greater burden on the entirety of the household. The reduced length of ITS compared to HTS also has the potential to produce higher completion rates, particularly for members of larger households who would otherwise experience significant survey fatigue.

Despite the benefits of ITS, household-based sampling frames tend to be more common and have traditionally been used in travel surveys. This has partly been a result of the previous dominance of CATI surveys, although it also stems from a desire to consider the household context in the decision-making process. Travel decisions are, to a large degree, made within a household context due to the sharing of resources and household-level constraints. Conducting a survey at the household level allows individual trip-making, which is affected by income, car availability, and opportunities to share rides and household-based activities (e.g. joint shopping trips, serving dependents, household chores, etc.) to be accounted for [**TAC P2, 2.3.2**]. In spite of the traditional preference for household travel surveys, individual-based surveys are gaining traction in practice. Emerging survey methods, particularly smartphone-based surveys, are likely to be individual-based, as it may be difficult to get all the members of a household to download and run an application may prove to be a difficult task. Overall, the HTS vs. ITS question is one that will require further investigation moving forward.

7 DATA FUSION AND COMPATIBILITY

An important feature of the core-satellite approach to data collection is merging the fractional information obtained from disparate sets of data to provide a more complete image of the travel behavior of the population. In fact, the success of the paradigm depends on effective data fusion. This chapter provides a general framework for fusing disparate sets of data collected under the core-satellite collection paradigm. The framework does not aim to provide a definite guide for fusion, but instead to provide direction towards appropriate methods based on the fusion context and indicate areas for further study.

The data fusion process is defined based on its context of application. In marketing research, it is usually associated with "statistical matching" of records from different consumer surveys based on common variables amongst the data files. In intelligent transportation systems (ITS) research, it mainly refers to multi-sensor data fusion, where observations from different sensors are combined to better describe the state of the environment of interest. Within the core-satellite context, it can refer to a method of linking together the information of the core and the satellite datasets to obtain more comprehensive travel behavior of the population. Although data fusion has existed in the statistics community and the marketing field for over half a century, its application in the transportation survey field is relatively new. In the limited research is available, the focus is mainly on conceptual methods, with actual implementations rare [**2017 Data Fusion, 1**].

This chapter provides a framework for data fusion within the core-satellite approach to travel data collection. With this aim in view, the chapter first reviews some common fusion techniques, highlighting their scope and applicability. Next, the chapter presents a critique of passive data streams to highlight their potential application as supplemental data sources within the core satellite framework. Next the methods of data fusion are categorized based on their context of application. Finally, the overall framework for fusing multiple data sources within the core satellite framework is discussed.

7.1 Prerequisites for data fusion

One of the main objectives of the core satellite collection paradigm is to design satellite surveys that are compatible with and hence linkable to the core survey. A key benefit of such compatible satellite surveys is that they can be fused with the core survey to exploit the availability of core data collected for a relatively large sample of the population [**2017 Core Satellite, 3.4**]. In general, this compatibility can be ensured if the design of the satellite survey is informed by the conduct of the core survey, the purpose of the satellite survey and the capabilities that the surveyors hope to enable [**2017 Core Satellite, 3.2**]. As described in [**TAC P3, 3**] different datasets are compatible with each other when they refer to similar spatial, temporal or semantic contexts. These context specific compatibilities can be considered as prerequisites for precise data fusion, which the core satellite paradigm tries to ensure through informed survey design. [**2017 Core Satellite, 3.5**] describes general proactive ways to ensure such compatibilities, while [**2017 Core Satellite, 4.1.4, 4.2.4, 4.3.4 and 4.4.7**] describe specific methods for ensuring compatibilities of potential core-filling or satellite surveys with the core TTS.

Compatibility, however, may not initially exist when one attempts to fuse a set of disparate datasets together, especially data from different sources (survey data vs. passive data). In such cases, it is necessary to harmonize the datasets before the actual fusion process. The main objective of data harmonization is to minimize incompatibilities among the datasets so that the precision of the fusion process is not hampered. Van der Lann (2000) proposed 8 types of harmonization issues to consider, which are presented in [**2017 Data Fusion, 3.1**]. In addition, the section heavily draws from [**TAC P3, 3**] and Bayard et al. (2009) to list relevant techniques for ensuring data compatibility at the spatial, temporal and semantic contexts.

Another important prerequisite for successful data fusion is identifying the most appropriate matching variables among the datasets to be fused. In general, the common variables that have high explanatory power in their respective datasets should be selected as the matching variables. [**2017 Data Fusion, 3.2**] describes four methods to identify the most appropriate matching variables. These methods measure the differences between the common variables of the datasets and identify the most similar ones as the matching variables for the data fusion process.

7.2 Summary of data fusion methods

Fusion in the context of transportation survey data involves the integration of files from different sources, and typically follows a donor-receptor framework. In this framework, the donor file(s) contains information that the receptor file(s) does not have but preferably should have. Variables unique to the files are called specific variables, while variables existing in all files are called common variables. The data fusion problem involves inferring the missing specific variable(s) in the receptor file by making use of the observed relationships among the common and specific variables in the donor file. Further description of this framework can be found in summarized in [**2017 Data Fusion, 2**].

Fusion methods pertinent to travel data have been categorized based on different underlying principles. The following sub-sections summarizes the different classes of data fusion methods based on (1) matching process of the common variables; (2) parametric features of the fusion methods; (3) level of aggregation of the fusion outputs.

7.2.1 Categorization based on matching process of common variables

Based on the matching process of the common variables, data fusion techniques are classified into two categories (Bayart, et al., 2009; D'Ambrosio, et al., 2007; Gilula, et al., 2006): (i) matching with certainty and (ii) matching with uncertainty. While summarized below, full details are provided in [**TAC PIII, 4.1 and 4.2**] and [**2017 Data Fusion, 4.2.1**].

(i) Matching with certainty/exact matching:

If common variables can be matched with certainty (e.g. identical ID, zone, or postal code), then exact matching or record linkage occurs. See [**TAC PIII, 4.1**] for some use cases of this basic form of data fusion in the travel survey context. Exact matching does not require statistical measures since records from donor and receptor files belong to the same individuals. The assumption underlying this method is that the matching keys or the unique identifiers across datasets are of good quality. However, most travel survey datasets do not have unique identifiers owing to privacy concern of the respondents; as such, this method has limited applicability in the travel survey context at the disaggregate level.

(ii) Matching with uncertainty/statistical matching:

If common variables are slightly different, but samples from the data files are still drawn from the same population, statistical techniques are required to determine the closest possible match. This process is called statistical matching. Since the common variables among the datasets do not match exactly, the analyst needs to use the joint distribution among the common and specific variables estimated from the donor dataset to statistically impute values for the receptor specific variables. There are two broad approaches for matching with uncertainty:

Explicit method:

This method of data fusion is based on variables in the datasets. At first, a mathematical model is developed to predict a target variable as a function of a set of common variables using the donor dataset. Then this model is applied to impute the missing target variable in the receptor file. The structure of the model depends on the type of the target variable. For a continuous target variable, linear regression, non-linear regression and non-parametric regression are techniques that can be used. In the case of a discrete target variable, logistic regression and binomial regression are candidate procedures.

Implicit method:

This method of data fusion is based on individual records of the datasets. It involves finding for each record in the receptor file, one or more donor records that are as similar as possible; next, the values of the target variable(s) are transferred using some procedure from the donor to the receptor individual (Bayart, et al., 2009). Two important concepts associated with this method are: (1) identifying the most similar donor and receptor pairs (generally using distance functions) and (2) using a suitable method to transfer the value of the donor target variable to the receptor so as to minimize the total mismatch among the target and donor common variables (usually weights are used for this purpose). Examples of implicit methods of data fusion include hot-deck imputation and k-nearest-neighbours imputation.

Based on the number of times each donor record is taken for matching, Rodgers (1984) further classify the implicit method into unconstrained and constrained matching. For unconstrained matching, there are no restrictions on how many times each donor record is taken for matching or whether each donor record must be used for matching or not. It has an advantage of allowing for the closest possible match between records. However, the matching file does not preserve the marginal distribution in the original files; hence, the result is biased [**2017 Data Fusion, 4.2.1**]. To avoid this problem, in the constrained matching technique, multiple donor records are used to compute weighted values for the target variables, where these weights are computed so that they reproduce both the original receptor observation weights and the original donor observation weights. The original weights are therefore preserved, leading to less-biased fused records compared to unconstrained matching. The constrained method, however, has some limitations. It cannot guarantee the closest match between donor and receptor files. Moreover, the "exploded" files contain repeated records and, therefore, do not represent the population values (**2017 Data Fusion, 4.2.1**). Finally, D'Orazio, et al. (2006) suggest the computational cost for this algorithm is heavy. Nonetheless, constrained methods are preferred to unconstrained methods since failing to constrain the marginal distributions of the original files in the matching file can produce significant bias in the estimation of the target values.

7.2.2 Categorization based on parametric features of the fusion methods

D'Orazio (2013) identify three approaches to data fusion based on the parametric features of the methods involved: (i) parametric, (ii) non-parametric and (iii) mixed approaches. The following sub-sections will provide an overview of each of these approaches, with full detail in [**2017 Data Fusion, 4**].

(i) Parametric approach

If the joint distribution of variables is assumed to be one of the known probability distributions, then the fusion problem is parametric and has micro and macro objectives [**2017 Data Fusion, 4.1**]. The macro objective is concerned with the estimation of covariance of the specific variables. Typically, maximum likelihood estimation is used for continuous variables, whereas the log-linear model is used for categorical variables [**2017 Data Fusion, 4.3**]. On the other hand, the micro objective focuses on the estimation of regression coefficients. Two steps are involved: first, file concatenation is performed (Rubin, 1986), followed by the use of conditional mean matching (e.g. with regression imputation) or draws from the predicted distribution (e.g. with stochastic regression imputation) to impute the missing variables (D'Orazio, et al., 2006). Overall, the parametric approach is parsimonious; however, it may be unreliable if the regression model is incorrectly specified (D'Orazio, et al., 2006).

(ii) Non-parametric approach

If no probability distribution of the variables is specified, then the process is non-parametric (Leulescu & Agafitei, 2013). This process does not require specifying a model in advance. It is strictly linked to the nonparametric imputation procedures applied to fill in missing values in the merged dataset. As per this definition, exact matching or record linkage method is the simplest and the most accurate of the non-parametric approaches. More complex examples include random hot-deck imputation, distance hot-deck imputation and rank hot-deck imputation. Details of these methods can be found in D'Orazio et al. (2006).

As the non-parametric approach does not require a model, it is free of the disadvantage of unreliable results stemming from model misspecification. It, however, requires a selection of a subset of the common variables (using grouping or matching). If variables with low predictive power on the target variable are selected, they may negatively influence the distances leading to biased output (D'Orazio, 2013).

(iii) Mixed approach

Mixed approaches usually contain a parametric step to impute the values of the missing variables, followed by a non-parametric step to find the closest match and derive a synthetic data source. Thus, the mixed method joins advantages of both the approaches. The non-parametric 2nd step offers protection against model misspecification in the 1st step and simultaneously avoids the problem related to computing the distances by considering several common variables (D'Orazio, 2013).

7.2.3 Categorization based on the level of aggregation of the fusion outputs

The National Academies of Sciences, Engineering, and Medicine (2017) discuss four categories of statistical methods that can be used to combine data from different sources. The categorization is mostly based on the availability of linking variables and the level of aggregation of the fusion outputs (fusing aggregate statistics vs. individual records from multiple data sources). These categories are (i) record linkage, (ii) multiple frame methods, (iii) imputation-based methods and (iv) modeling techniques.

(i) Record Linkage

This method associates records from different data sources that are thought to belong to the same entity using linking variables. Record linkage can be either deterministic or probabilistic. In deterministic record linkage (DRL), a set of linking variables is specified and records must agree on all the linking variables in that set to be considered a match. The number of linking variables may vary from one to many. DRL works well if the linkage variables have no errors or missing values and uniquely identify entities in the population. In practice, however, linking variables are often subject to errors, necessitating probabilistic record linkage (PRL) which quantifies the errors in some way (Fellegi & Sunter, 1969). For example, the extent of similarity in the linking variables may be evaluated using the ratio of the probability that two records would have this agreement if they are a true match, and the probability that two records would have this agreement by chance if they are distinct entities (National Academies of Sciences, Engineering, and Medicine, 2017). Larger values of the ratio indicate that the records are expected to have the specified agreement pattern if they are a true match.

Record linkage has the advantage of increasing the number of variables for records in a survey, decreasing respondent burden, augmenting the number of records available, validating responses to a survey, filling in values for missing data, and assessing or improving sampling frame. Gathering more information, however, about individuals by linking multiple datasets might pose privacy concern. The record linkage approach has limited applicability if the linking variables have errors (linkage error can lead to biased conclusions) or if the data sources have little identifying information. Although statistical methods can account for linkage bias, these cannot remove the bias in key variables of interest (National Academies of Sciences, Engineering, and Medicine, 2017).

(ii) Multiple frame methods

These methods are useful for combining aggregate statistics from different data sources. Lohr (2011) describes methods to obtain unbiased estimates from multiple frame surveys. Most of these methods involve reducing survey weights for observations that are in both frames so that they are not double-counted. Multiple frame methods are mostly applicable for surveys in which the frames cannot be consolidated before sampling (National Academies of Sciences, Engineering, and Medicine, 2017). These methods provide better representation of the population while being less intrusive than record-linking in terms of privacy. The methods can also account for potential differences in the survey modes.

(iii) Imputation-based methods

These methods are used to combine information from different individual record-level sources. Here, existing information is used to fill in missing values caused by survey non-response or file concatenation [**2017 Data Fusion, 4.5**]. The imputation-based methods can be either parametric or non-parametric. In parametric methods, a multivariate model predicts the missing values using the information in the observed values. In non-parametric methods, a missing value of a variable in a record is replaced by the corresponding value from another data record using random hot-deck, rank hot-deck or distance hot-deck procedures. These techniques create only one complete dataset while ignoring the uncertainty of the process of predicting missing values. As such, these are categorized as single imputation. Alternatively, a multiple imputation technique can be used to include the extra variability from the imputation predictions in standard errors for statistics. See [**2017 Data Fusion, 4.5**] for details of the steps involved in multiple imputation. The goal of multiple imputations is not to produce the "correct" missing values, but instead to generate datasets that provide statistically valid inferences of parameters from the incomplete data (Rudra, 2014).

Imputation-based methods strongly rely on assumptions about the mechanism producing the missing data and on predictive models for the missing values. As such, the assumptions have to be thoroughly checked and the sensitivity of inferences to the assumptions needs to be explored. Nonetheless, these methods provide a complete dataset by taking advantage of the relationships among all variables that are present on the files. By doing so, these methods can infer beyond the scope of each data source (National Academies of Sciences, Engineering, and Medicine, 2017).

(iv) Modeling techniques

Modeling techniques can be used to combine aggregated statistics with each other or with individual record data when the data sources measure different variables. The techniques can also combine statistics estimated from probability and non-probability sources. Generally, Bayesian hierarchical or multilevel models which incorporate differing error structures in the estimates are used to combine information in this method. An inherent weakness of the method is the model assumptions, which need to be tested and justified (National Academies of Sciences, Engineering, and Medicine, 2017).

The danger of miss-specified models leading to biased estimates has discouraged the use of modeling techniques as a tool to combine multiple data sources; however, with increasing non-response and a need for data fusion, making modeling assumptions are becoming essential (National Academies of Sciences, Engineering, and Medicine, 2017). As such, this method needs to be developed further via innovative modeling techniques and proper testing of related assumptions.

Although the classifications schemes described above tackle the data fusion problem from different perspectives, the methods adopted for the actual fusion process are not mutually exclusive. While the explicit methods are parametric in nature, the implicit methods are mostly non-parametric. On the other hand, imputation-based methods can be both parametric and non-parametric (hence explicit and implicit). Overall, the review of the classification schemes indicates that the data fusion method chosen for a particular context depends of the nature of the datasets to be integrated and the end goal of the fusion.

7.3 Critique of Passive Data

Passive data sources as discussed in **Final 2.2** provide revealed preference travel data continuously with little respondent burden. Among the different passive data sources available at present, the most useful ones from a transportation planning perspective are transaction data sources (e.g. smart card automated fare collection systems (SCAFC)) and fixed road-side technologies (e.g. traffic counters and video streams). This section provides an overview of the different passive datasets that have been used in transportation-related applications, with the goal of assessing their potential use within the proposed core-satellite data collection approach.

7.3.1 Smart card data

In relation to the travel survey context, the greatest advantage of smart card data is that they are collected continuously; hence, these data can be compared between multiple time frames and over longer periods of time than traditional survey methods. These data, however, are limited to only public transit services and cannot be generalized for other modes of transport. They also lack personal and household level socio-demographic information and trip purpose. Moreover, these data provide only boarding and alighting locations and times, but not actual trip origins and destinations. Owing to these limitations, transit smart card data have mainly been used to analyze the travel behavior of transit users and to derive origin-destination matrices of the transit network. **[TACPII, 4.4.1.1]** and **[2016 Passive, 2.1]** present some of the most common applications of smart card data from around the world. Even these limited applications require several assumptions regarding the alighting location (if the SCAFC has no tap-off), the transfer distance and time, and the actual trip origins and destinations. [**2016 Passive, 2.1**] provide the basic assumptions included in most smart card applications. These assumptions make the accuracy of the developed OD matrices questionable. Nonetheless, the large quantity and continuous nature of smart card data make it suitable for generating and updating transit OD matrices. For example, Barry et al. (2002) update existing OD matrices derived from smart card data by repeating the OD matrix generation process over different points in time. Such updating allows changes in travel pattern to be tracked over time. Smart card data also have the potential to supplement classical HTS data (Bayart, et al., 2009), thereby allowing detailed transit behavior modeling. See [**Final, 7.4**] for more detail on this potential application.

7.3.1.1 PRESTO

To evaluate the potential for smart card data in the TTS region, a preliminary analysis was conducted on datasets from the regional smart card fare collection system in the GTHA, PRESTO. PRESTO was introduced with a goal of creating an integrated transit fare system amongst all agencies in the GTHA. At the time of this report, all 10 transit agencies had implemented the PRESTO system on their vehicles and in their stations. There are, however, wide variability in how and the degree to which PRESTO systems have been deployed (an overview of the system and these differences can be found in [**2018 PRESTO, 3**]).

Two data sets of raw PRESTO transactions were provided to the team, covering periods in March and October-December 2017. They were used to examine the current capabilities of PRESTO data using GO Rail (requiring both tap-on and tap-off for riders) and Hamilton Street Railway (only tap-on) transit systems. The analysis included use of automated vehicle location (AVL) data to improve [**2018 PRESTO, 4.4**] or fill in missing location details [**2018 PRESTO, 6.1**] for transactions, inference of alighting location for a tap-on-only system [**2018 PRESTO, 6.2**], and creation of OD matrices [**2018 PRESTO, 5**].

While full details are presented in that report, there are some key findings that have relevance with respect to its potential use within the core-satellite framework for the TTS:

- The ability to infer trips of riders from transactions is heavily dependent on the penetration of PRESTO; offering other fare payment types will compromise the ability to generate reliable OD matrices, particularly if there is bias in adoption
- With tap-on-only systems, unlinked trips will continue to be an issue, particularly for infrequent/non-commuting trips; even full adoption will not eliminate this issue
- The lack of precise GPS points attached at the time of transactions being recorded present a hindrance to accurately locate transactions and reconstruct trips; instead, PRESTO device-to-vehicle mapping tables that are often not up-to-date are required to estimate stops via fusion with AVL data
- The lack of presence of schedule data input into the PRESTO system complicates data processing by requiring more assumptions to associate transactions with specific routes
- Missing first and last leg information results in transit OD matrices from PRESTO transactions that do not align with those produced from TTS transit trip data; this will remain a challenge for its use either as a replacement or supplement to TTS OD matrices

7.3.2 Bluetooth data

Each Bluetooth device has a universally-unique machine access control (MAC) address which allows it to be accurately identified and tracked from a distance of up to 100 m at relatively low marginal cost [**2016 Passive, 3.0 & 3.2**]. This has inspired researchers to investigate the potential of Bluetooth devices for a variety of applications

- Tracking routes of individual vehicles and pedestrians
- Measuring real-time changes in congestion levels by estimating travel times
- Calculating traffic speed and volume
- Creating OD matrices

Details on these applications can be found in [**2016 Passive, 3.1**]. The studies show that although Bluetooth data has high precision, it suffers from poor detection rate. For example, the Bluetooth receivers detect only 5% and 2.5% of the actual pedestrian volumes in Montreal and Seattle, respectively (Malinovskiy, et al. 2012) and 2% – 3.4% of all vehicles on the I-65 highway (Haghani, et al., 2010). The poor sampling rate results from low penetration of active Bluetooth devices among traffic and the power requirement of the receivers which lead to their installation near intersections (where traffic interactions affect the resulting data) [**2016 Passive, 3.2.2**].

Moreover, Bluetooth data collection is mostly suitable for densely populated locations such as downtown, where the detection accuracy of devices is higher. This results in more accurate estimations of origins and destinations compared to sparsely inhabited areas. In the latter, the number of receiving stations required for accurate traffic detection increases considerably, thereby making the overall data collection costly. From these discussions, it is evident that currently the drawbacks of Bluetooth data outweigh its benefits. As such, this method is not ready for use within a core-satellite HTS framework at this moment.

7.3.3 Cellular data

Among the different passive data sources, cellphones have the highest penetration rate [**2016 Passive, 4.2**]. Thus, the cellphone traces can be analyzed to produce travel information (location and time) for a large sample of the population. Since the cellphone data is collected somewhat continuously over time (when a phone uses service such as call, text or data), it can be used to frequently update OD matrices. Moreover, cellphones are owned on an individual basis. Hence, they can track both vehicular and traveler movements [**2016 Passive, 4.2**]; this can be contrasted with smart cards which are relevant only for public transit services. Different studies have revealed the potential of cellular data to generate OD matrices and to validate speed and travel time estimations. Details of some of these studies can be found in [**2016 Passive, 4.1**].

There are, however, problems with the use of cellular data in travel demand applications like an HTS. Cellular data suffers from poor location accuracy (making it more feasible for long distance trips), non-periodic location data recording (data recorded only when cellphone service is used), and possible demographic bias among users of different service providers. Also, like all other passive sources, cellular data lacks associated trip and demographic information.

Nonetheless, it has enough potential to be used as a supplemental data source within the TTS context [**2016 Passive, 4.3**]. The suitability stems from the fact that most of the commuting trips in the GTHA are long-distance trips from sub-urban areas to downtown core. As a result, cellular data may be sufficient in providing accurate origins and destinations; however, verifying this suitability requires further research. Also, any demographic bias towards certain cell phone carriers should be addressed when considering cellular data as part of the TTS; this area requires further research [**2016 Passive, 4.3**].

7.3.4 GPS data

In-vehicle and portable GPS units are another passive source of continuous spatial and temporal travel data. They are highly accurate and allow for the collection of data regularly at short intervals. Recently, the GPS system installed in smartphone devices are being increasingly used as a passive data source to trace individual movements, either as part of a smartphone survey, or via third-party apps that resell customers' location info. With the increasing smartphone penetration among the population, the built-in GPS systems can be used to provide travel information for a considerably large sample. While the data quality of the smartphone GPS systems should be similar to dedicated GPS devices, in practice this is not the case because of battery life concerns on smartphones and frequencies of use of third-party apps when data is collected indirectly. In order to minimize battery drain, GPS data are usually logged at longer intervals in smartphones than in dedicated GPS units, thus leading to a loss of location data [**2015 Smartphone, 3.1.1**]. In general, GPS can address trip under-reporting issues associated with traditional survey methods [**2016 Passive, 5.1**]. However, the data suffers from issues such as cold starts, missing short trips, and urban canyon effects. Also, long-term data collection is rare, mainly due to privacy concerns [**2017 Core Satellite, 5.1**].

In terms of application, currently the in-vehicle GPS data is heavily biased towards freight vehicles [**2016 Passive, 5.1**]; however, it also has great potential to track taxi and Uber/Lyft travel patterns, given that these services heavily rely on the GPS system for their operation. A study conducted by Schäfer, et al. (2002) tested the feasibility of producing OD matrices using GPS data of taxi fleets from Berlin, Nuremberg and Vienna; the authors found the source to be viable for producing OD matrices for taxi services. The GPS traces from smartphone devices are being used for detailed travel behavior modeling, such as route choice modeling (Hood, et al., 2011; Bierlaire, et al., 2010). Hence the GPS data from in-vehicle and portable systems and from smartphone devices can serve as a supplemental source or independent satellite within the core satellite framework.

7.3.5 Other passive techniques

Other passive techniques relevant to travel data collection include magnetic loop detectors, video streams, and automatic passenger counters (APCs). These are discussed in detail in [**TAC PII, 4.4.1.2 & 4.4.1.3**], which highlights their benefits and potential uses. Loop detectors and video cameras are mainly used for traffic count and speed estimation, real time travel time estimation and incidence and congestion level detection. APCs provide automated counts of passengers boarding and alighting from transit vehicles. The data obtained from these additional passive sources are primarily used for survey data validation and validation of regional travel models which are estimated and calibrated from travel survey data. For example, cordon count data collected by agencies are used to validate TTS data and calibrate the regional travel demand model – the GTA model. In addition, these data can be used in count-based data expansion as discussed in detail in [**Final, 7.4**].

7.3.6 Recommendations

From the above discussion it is evident that passive sources have the benefit of providing travel data accurately and continuously with little respondent burden. They can, therefore, be a means by which to reduce trip under-reporting and proxy bias issues of traditional survey methods. Passive sources, however, do not obtain, for example, information on trip companions, trip purpose (difficult to infer in dense urban areas), fares paid and parking information. As such, in its current form, passive data has greater potential to be used as supplemental/complemental information in the core satellite framework than as a replacement to traditional sources. For example, they can be used to periodically update developed OD matrices or to model ridesharing or ride-hailing travel patterns. Also, if the core has limited data on public transit use, smart card data can be added as a satellite source to enable detailed transit behavior modeling. These potential applications, however, would require the development of appropriate fusion techniques for inferring trip origin, destination, travel mode, and trip purpose. Finally, it should be noted that procuring passive data from third parties like cellphone providers or taxi fleet companies would require high cost and negotiation. These can only be justified if the data is procured as part of a bigger initiative of overall transportation planning and not solely for the purpose of an HTS.

7.4 Framework for data fusion

This section categorizes the data fusion methods discussed in [**Final, 7.2**] based on the situations that could be encountered while fusing multiple datasets. Generally, any fusion process starts with identifying appropriate databases by examining their characteristics. Next, common (or similar) data elements are identified that facilitate fusion. Finally, datasets are analyzed and integrated using a suitable fusion method.

Different situations might arise during the fusion process depending on the presence of exact identifying variables in the datasets, and whether the fusion integrates aggregate statistics or individual records of the datasets to form a complete combined and synthetic dataset. These criteria impose varying levels of complexities to the fusion process. Based on these complexity levels, this section categorizes the reviewed fusion techniques into three classes: (i) Direct matching or Record linkage, (ii) Statistical matching using imputation or modeling techniques and (iii) Generating synthetic populations with valid travel behavior.

7.4.1 Direct matching/Record linkage

The most basic form of data fusion involves combining multiple data sources that usually belong to the same sample (or its subset). In this process, raw individual-level records in the datasets can be directly matched via exact identifiers. Such record linkage produces a combined dataset containing more variables than the original sources. All the variables included in the synthetic dataset are observed information, and not modeled or imputed outputs. Hence, this method has high degree of reliability and accurateness; however, it is feasible only if the records from multiple data sources can be matched via IDs or the linking process is embedded within the survey sampling and recruitment phases. Some of the common use cases of this method in the context of travel surveys include the following:

(i) Matching travel survey records with aggregate demographic, land use or other zone-based attributes based on census tracts or traffic analysis zones.

In this case, the common variable is the zone and allows the donor target variables to simply be copied to the receptor record. Additional common variables, of course, may exist (e.g. same income group) [**TAC P3, 4.1**].

(ii) Linking records of core-extension surveys with those of the core HTS to gather detailed information from a random sub-sample of the population.

In this case, the linkage is provided by the sampling and recruitment techniques adopted for the core-extension surveys. As described earlier in [**Final, 4.2.4 and 4.4.5**] respondents for core-extension surveys are sampled directly from the households participating in the core survey immediately after the completion of the core HTS. Such direct recruitment allows for explicit linkage among the survey records, thereby providing more comprehensive information for the core-extension participants.

(iii) Linking records of the linked satellites with the core HTS to gather detailed information from a targeted sub-sample of the population.

Similar to the core-extension surveys, the respondents for the linked satellites are sampled from households participating in the core survey. Since, however, the surveys are conducted at different times, household-specific identifiers are needed to establish the explicit link between surveys.

(iv) Joining RP and SP data collected from the same individual by matching individual-specific identifiers.

Individual records from an RP-SP survey can be matched with certainty by a unique ID, as survey respondents answer both types of questions. In this case, the fusion occurs within the parameters of a joint model estimated using the data from both the RP and the SP components of the survey. Specifically, data fusion is mainly carried out via the estimation process of the scale parameters that correct the systematic bias of the SP data [**2017 Data Fusion, 5.2**]. Details on joint RP-SP model estimation from the perspective of data fusion can be found in [**TAC PIII, 4.3**] and [**2017 Data Fusion, 5.2**].

7.4.2 Statistical matching using imputation or modeling techniques

In this category, the source files do not have record-specific identifiers; as a result, direct record linkage is not possible. Rather, the missing/additional information in the combined dataset is obtained through a statistical matching procedure involving imputation or modeling. This category is less accurate than record linkage as the additional variables included in the synthetic dataset are not observed information, but modeled or imputed outputs. This category, however, offers greater flexibility than record linkage in terms of the level of aggregation of the fusion output. Different methods within this category can combine aggregate statistics from multiple datasets or they can combine individual records of the data sources so that a complete synthetic dataset is created. Some of the common use cases of this category in the context of travel surveys are as follows:

(i) Data expansion

Because of the inability to collect information from the entirety of a population, data expansion is necessary when studying the behavior of the population. In the context of household travel surveys, data expansion is used to apply the information and insights obtained through the survey sample to the general population. Thus, it is the most common form of data fusion, and is based on the existence of a common spatial context [**TAC PIII, 3.0**]. Usually, a population census is used to expand transport datasets containing socio-economic variables [**TAC PIV, Appendix**]; however, attempts have been made to use targeted marketing data to expand travel survey data in lieu of census data [**2017 Core Satellite, 5.5**]. In the Canadian context, the CANSIM Monthly Urban Transit survey has the potential to be used for expanding transport datasets with socio-economic data [**TAC PIV, Appendix**]. It is important to note that data expansion is simply a method to estimate the travel behavior of a population based on the data collected from a random sample of the population. It cannot address issues of representation in the original sample. In fact, expanding a biased sample would result in a biased travel behavior representation of the population.

Data expansion methods involves weighting the sample to match census control totals or counts, where the weighting factor is simply the inverse of the selection probability of the individual in the sample from the sample frame. The control total-based expansion is the most common expansion method applied in practice for most large-scale travel surveys. For example, the 2011 TTS data were expanded in two stages to match the distribution of dwelling units in each Forward Sortation Area (FSA) and the distribution of age cohorts in each municipality [**2017 Core Satellite, 3.1.2**]. Similarly, person-level control totals obtained from the 2008 American Community Survey, stratified by geographic region, were used to expand person-level data collected in 2011 NHTS whereas, household weights were determined based on selection probability [**2017 Core Satellite, 3.7.1**]. If the sample data is to be expanded to match multiple control totals such as the distributions of age, gender, dwelling type and household income, Iterative Proportional Fitting (IPF) is needed; this method was used in the 2016 TTS. In IPF, the detailed joint sample distribution is 'updated' using aggregate population 'marginals' until it matches the aggregate population totals (Beckman, et al., 1996). In some cases, the survey sample is weighted to match counts instead of census control totals, which is termed as count-based expansion. Typically, traffic counts obtained from intercept surveys or boarding and alighting counts obtained from APCs are used for this purpose.

(ii) Combining core-filling survey with the core to improve population representation

As described in [**Final 3.3**], the core-filling survey collects the same information (at a minimum) as the core survey, but from a certain subpopulation that is underrepresented in the core. As such, the sample frames of the surveys are not independent of each other. Instead, they have a certain degree of overlap. Accordingly, the data fusion method adopted for integrating these samples mainly involve weight adjustments, where survey weights for observations that are common to the sample frames are reduced, to account for the multiple chances of selection. In this way, the fusion method can reduce non-response and proxy biases in the estimated statistics. This technique is similar to the multi-frame method discussed earlier in [**Final, 7.2.3**]. As for the micro objective of integrating the samples to form a combined dataset, at first the independent and the overlap portions of the sample frames need to be identified. Following this, the fusion process is essentially file concatenation for the independent records, whereas for the overlap option, only one record (preferably from the HTS) should be included in the combined dataset. Verreault and Morency (2018) applied this method to correct the under-sampling bias of 20-29-year-old students by integrating a web-based student travel survey and a phone-based HTS.

(iii) Combining independent survey with the core to capture detailed travel behavior

As mentioned in [**Final, 4.2.4**] the frame selection for the independent survey varies with the survey purpose. Accordingly, the method adopted for integrating the independent survey sample with the core sample varies with the purpose of the fusion. If the objective of the fusion is to construct a complete synthetic dataset containing all the variables of interest from the independent survey and the core survey, then an imputation-based approach described in [**Final, 7.2.3**] can be adopted. In this approach, parametric and non-parametric methods are used to obtain the missing values of the combined dataset by exploiting information in the source files. Creation of such a complete synthetic dataset might be necessary for developing microsimulation models used in policy analysis.

However, if the objective is to use the information collected by the independent survey to model unobserved travel behavior of the core, the modeling approach to data fusion (described in [**Final, 7.2.3**]) might be more applicable. For example, an independent active mode survey collecting details of bicycle trips along with demographic information of the cyclists may be used to develop a bicycle route choice model in terms of origin and destination locations, departure time and socio-demographics of the cyclists. This model can then be used to model the route choice of the bicyclists in the core sample. In this way the information from the independent and the core samples can be combined with each other through modeling techniques, without necessarily producing a complete synthetic dataset.

(iv) Using passive data to update OD matrices

From the discussions presented in [**Final 7.3**], it is evident that the greatest potential of passive data in its existing form lies in periodic/continuous updating of existing OD matrices to capture evolution of travel pattern with time. However, a caveat with this technique is that control totals from the census are not updated so frequently. Hence the updated matrices would have inaccuracies stemming from expansion using out-of-date control totals.

(v) Imputing socio-demographics and trip purpose of passive data to better capture travel behavior

The core survey captures a representative sample of the overall population. As such, even in large-scale HTS like the TTS, the number of observations of less chosen alternatives like ride-hailing and ridesharing services (taxi, Uber, Lyft) might be too small for mode-specific travel behavior analysis. However, passive trip information is available with the operating companies of these services, which contain accurate spatial and temporal trip information. However, the data lacks socio-demographics of the users and the trip purposes. Similarly, smart card data gives continuous location and time information, but it also lacks personal and household level socio-demographic information and trip purpose [**Final, 7.3**]. Hence it may be necessary to impute these missing information in the passive data sources so that they can be used for analyzing detailed travel behavior. The most relevant fusion approach in this regard would be the modeling technique. Here, the model developed for imputing the missing information could be validated using core data and then the validated model could be used to impute socio-demographics and trip purpose. Such an approach was tested by Alsger et al. (2018) to impute transit trip purpose using smart card data.

7.4.3 Creating synthetic population having observed travel behaviour

With increasing quantity of transportation data and computational resources, it is possible that data from multiple sources are fused together to create a synthetic population that is statistically representative of the real population and has travel behavior like the real population. Currently, synthetic populations are created by iteratively updating a disaggregated dataset (usually census public use microdata or HTS data) so that it matches the marginal totals of the aggregated census data (as well as other data sources). Iterative proportional fitting (IPF) is the standard procedure to develop such a synthetic population (Beckman, et al., 1996), although recently new computational methods for synthesizing more and finer categories of socio-demographic attributes are being proposed. Among these, the "sample-based" methods (Prichard & Miller, 2011) rely on census data as the sole reference sample for the synthetic population, whereas the "sample-free" method (Namazi-Rad, et al., 2017) uses a heuristic approach that does not solely rely on the census [**2017 Data Fusion, 5.1**]. The convex optimization method allows prioritizing marginals through subjective weights, in contrast to the equally important marginal concept of IPF (Vovsha, et al., 2015). Recently, Bayesian networks are being used in population synthesis to fuse multiple data sets' information together and to increase the heterogeneity, representativeness, and usefulness of the synthetic populations.

Nonetheless, some degree of replication of the same households with the same characteristics does occur while generating a synthetic population from aggregate marginal totals. To overcome this problem, emerging passive data sources can be exploited. Passive data sources that can reach almost complete penetration of the population can be used instead of weight-based updating techniques in a process that applies information and insights obtained through the survey sample to the general population.

Once the synthetic population is generated, it can be assigned valid travel behavior models to simulate the trip patterns of the entire population. The travel behavior models need to be estimated and calibrated using observed behavioral data and then validated using ground data (such as traffic counts and transit boardings). Such a synthetic population having valid travel behavior could be used for scenario analysis to better understand how people may be impacted by potential transportation interventions.

7.4.4 The data fusion framework

The data fusion framework discussed throughout this section has been summarized in Figure 7-1. The diagram shows considerations required for different steps of the fusion process, specific to different complexity levels. It presents multiple fusion use cases that are relevant to the core satellite collection paradigm or to the HTS context in general.

Figure 7-1 gives a roadmap towards developing a comprehensive data fusion framework in the context of HTS. Some of the use cases presented in the figure have been elaborately researched throughout the course of this project or in the literature; hence, the framework suggests specific feasible fusion techniques feasible. In other cases, further investigation is required to determine the most appropriate technique; the framework alludes to potential avenues of exploration. The outputs, however, of the proposed framework need to be validated to ensure the quality of the associated data fusion procedures.

The validity of the outputs of the proposed fusion framework can be tested using the four-level validity criteria of Kiesl & Rässler (2006). These criteria are discussed in detail in **2017 Data Fusion, 6**. The first and the lowest level of validity is to preserve the original data sets' marginal distributions of variables in the fused dataset. The second level is to preserve correlation structures, which can only be achieved assuming that specific variables are conditionally uncorrelated. The third level is to preserve joint distributions, which is subject to the Conditional Independence Assumptions. The fourth and the most specific level is to preserve true values of the imputed variable in the fused file with certainty. Kiesl et al. (2006) suggest that at the minimum fusion methods should ensure the preservation of marginal distributions and correlation structures (first two levels), as achieving the last two levels are constrained mathematically and can be potentially misleading [**2017 Data Fusion, 6**].

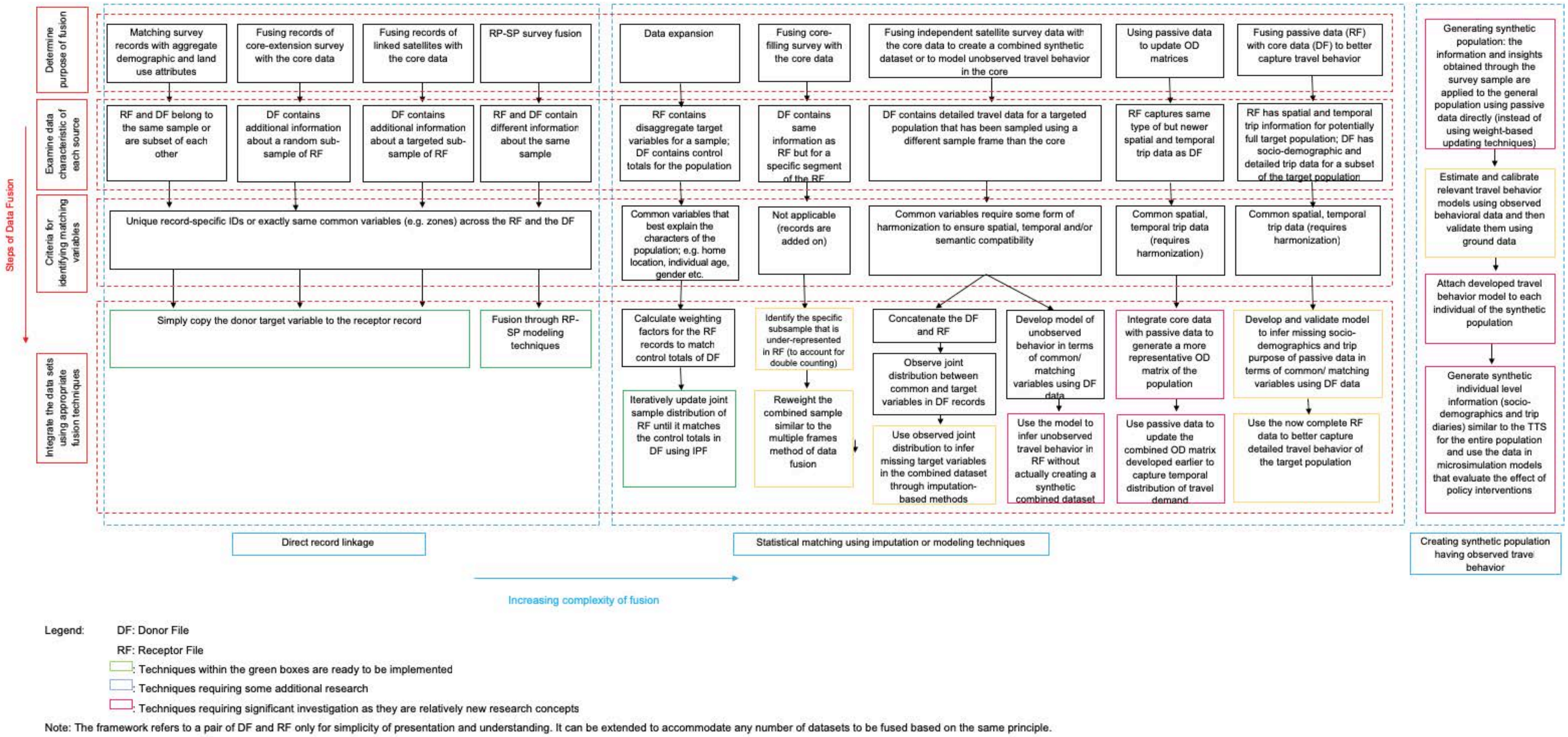

Figure 7-1 Framework for data fusion (Based on purpose of fusion)

8 TRAISI - MOVING FROM THEORY TO PRACTICE

The core-satellite approach is an acknowledgement of the need to undertake many surveys in order to achieve a representative and in-depth picture of travel demand. It is also a framework to do so in a coherent and connected fashion. This, however, is easier stated that executed; without a carefully designed survey system what could result is a collection of disparate surveys with data that are difficult to fuse. To these ends, a survey design and execution platform, the TRavel and Activity Integrated Survey Instrument (TRAISI) is in development. TRAISI aims to fill a need for a practical way to conduct core-satellite surveys in the immediate, and eventually act as a data fusion, retrieval and analysis platform.

8.1 Version 1

The focus of the initial version of TRAISI [**2017 Web Report**] was not on the development of a core-satellite platform. Instead, it was used as a prototype system to investigate some research questions with respect to the design and execution of web-based surveys, in particular how to collect a detailed trip diary of a household. To this end, while a basic survey creation and management system was implemented, the front-end respondent interface was the aspect investigated. A few iterations of the trip question were designed, updated based on feedback from survey participants. An extension was also programmed to use the platform to conduct a stated preference survey. A summary of these conclusions can be found in [**Final, 5.2**] as part of the critique of CAWI systems.

8.2 Platform requirements

The goal behind the second version of TRAISI is to move towards the creation of a true core-satellite platform. This was as a result of the acknowledgment that the core-satellite framework was not a practical solution without a tailored software solution. A core-satellite platform has some key requirements, in addition to some basic features necessary for any survey-building and execution system. They are described in this section.

8.2.1 Basic web survey platform needs

- **Administration:**
    - **User groups**: To allow multiple research groups and agencies to host their own surveys (privately), and allow for internal management of groups.
    - **Survey building:** Designing of surveys, allowing for:
        - Addition/Removal of pages, question sections, and questions.
        - Configuration of question and setting of question options.
        - Household question to allow members to each answer their own set.
        - Multilingual.
        - Conditionals.
        - Question piping (answers displaying on text of subsequent questions).
        - Design of welcome, privacy policy and thank you pages.
        - Styling/theming of survey.
    - **Survey management**: Creation and management of surveys, as well as sharing.
    - **Survey execution:** Pilot testing and live execution of surveys, allowing for:
        - Individual and group (company/institution) codes.
        - Emailing to individuals and groups, including scheduling reminders.
    - **Monitoring:** Live results by question and overview of survey progress.
    - **Analysis:** Live filtering of results and production of matrices; display of results on maps and graphs in various forms.

- **Respondent:**
  - **Accessing a Survey:** Direct link or start survey with a code.
  - **Privacy Policy:** Be informed about goals and terms of the survey.
  - **Return and Resume:** Allow for exit and return back to prior location.
  - **Autosave and Validation:** Responses automatically saved with live feedback.
  - **Accessible:** Conform to government web accessibility guidelines.
  - **Easy Access to Assistance**: Be provided with both direct online help or be able to reach a survey representative easily for assistance.

8.2.2 Core-satellite platform requirements

To advance a standard survey platform to one that is capable of handling a core-satellite collection paradigm requires features not contained in traditional survey systems. These requirements revolve around 2 main areas:

- Integration of multiple survey modes and survey mode hybrids.
- Fulfilling pre-requisites for data fusion.

Conducting a multiple response mode survey is critical to maximize data quality, with different modes being found to work better for different demographics. Integration of multiple survey modes within a single survey requires an interface that can display different survey views, while allowing respondents to switch between the two seamlessly (e.g. start on CATI and finish on CAWI or vice versa). For older demographics, a hybrid system may be necessary via integration of call-centre functionality directly into the web-interface. This is necessary to provide assistance when these respondents are only reachable by mail or email. Seamless integration requires a system structure where data is independent of the view (e.g. web-survey vs CATI script vs in-person vs smartphone), eliminating the need for post-survey integration, which can be complicated. CATI integration requires, itself, a set of features that are unique to the mode (interviewer interface, interviewer and reviewer management).

Data fusion has a few pre-requisites **[Final, 7.1]**, broadly categorized as semantic, spatial and temporal compatibility. A core-satellite platform has to attempt to deal with these three areas. From spatial and temporal compatibility standpoints, this would include being flexible enough to allow for samples to be shared between surveys while having features that allow questions to be shown based on specific geographies. The highest degree of assistance, however, should be on the semantic compatibility side, where features can be included to help in wording, explanations and response option choices (i.e. pre-set lists of gender, occupation, fuel type, etc.).

8.3 Version 2

8.3.1 Transition from website to web application

The above requirements lead to a computing architecture and implementation for the second version of TRAISI that eschews a traditional static and page-by-page website for a web application. Web applications are websites that act like desktop applications in a browser; the site does not need to transition from page to page. Instead, the application maintains a connection with a backend web server, sending and retrieving data as needed to refresh content on the application. This allows for much smoother and quicker interactions for the user and the capability to significantly reduce load times.

8.3.2 Conceptual architecture

This web application structure allows for an expandable architecture to progressively add features to TRAISI version 2. Figure 8-1 provides a future-facing architecture for the platform. At the core is the TRAISI core Web Application Programming Interface (API). It acts as the central cloud-based server of TRAISI, housing all backend functionality, including storage of surveys and data, and any fusion and data analytics capabilities. The connecting interfaces shown surrounding the core Web API provide user-facing environments to design, conduct (while allowing for multiple modes) and analyse survey data, as well as allowing for external data sources (e.g. smart-card) to have end points to transfer data. This architecture allows for the platform to progressively gain functionality without interfering with other aspects. For example, basic survey design and conduct functionality can be programmed, without the need to immediately implement data fusion or analytics capabilities.

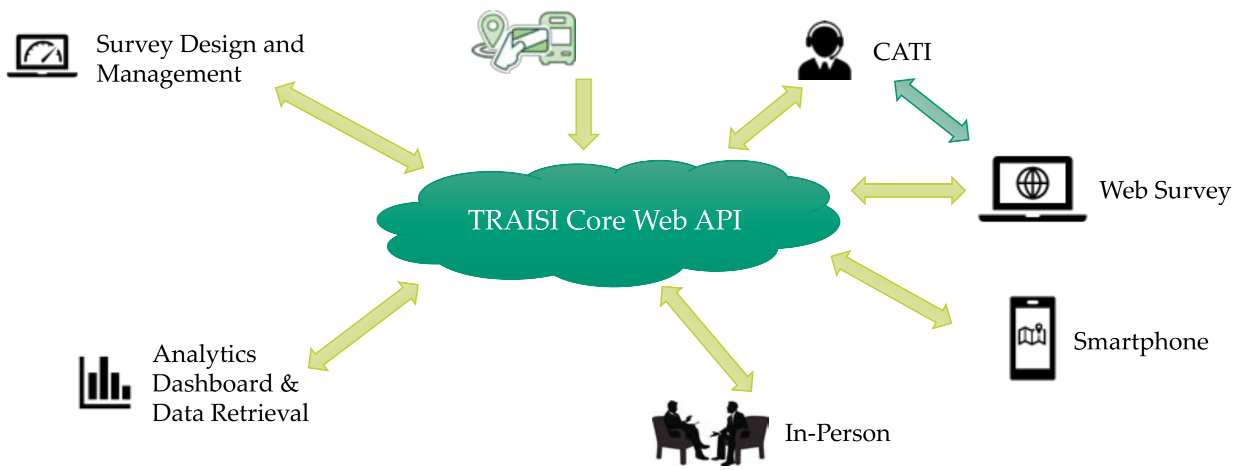

Figure 8-1 TRAISI Version 2 Conceptual Architecture

8.3.3 Key core-satellite features

There are many features required of a core-satellite platform like TRAISI. This section highlights five areas required to allow for TRAISI to handle a core-satellite design of the TTS: user groups, multiple survey modes, flexible survey execution, standards and compatibility and data platform.

User Groups In order for TRAISI to be a core-satellite platform capable of conducting a regional survey, it will be able to handle multiple user groups. This would allow representatives from different government agencies to access the core survey and conduct their own satellites as needed. This implicitly should allow surveys to be shared between user groups at varying levels to allow for surveys to be conducted together, or just shared to be a reference for another group's survey.

Multiple Survey Modes As stated earlier, a core-satellite platform should allow for multiple survey modes (CATI, CAWI, CAPI, smartphone) to be used for surveying. TRAISI will incorporate design best-practices based on research findings into the front-end designs (including satisfying accessibility requirements) and be stored using an integrated data model.

Flexible Survey Execution The core-satellite paradigm requires features that allow for flexible survey execution to handle the various types of connected surveys in the paradigm and allow for respondents to be sampled from for follow-up surveys. TRAISI aims to enable these capabilities via features of shared populations (where a survey can use respondents of another as a sampling source) and geographic-specific or institution-specific questions, necessary for core-extension and core-filling surveys, respectively.

Standards and Compatibility A distributed survey methodology like core-satellite requires features to assist in standardizing of terminology and question wordings to minimize biases and prevent issues of semantic incompatibility. TRAISI will uniquely incorporate a transportation ontology developed at the University of Toronto for this purpose; an ontology is a standard model of definitions and relationships.

Data Platform To deal with the many data sets inherent to the core-satellite paradigm, TRAISI will act as a data platform. While raw data output will still be available, this feature will allow for standard methodologies of data fusion and analytics to be incorporated and available for all end-users.

8.4 Current implementation

While the main takeaway of TTS 2.0 is the framework for the next generation of TRAISI, this framework was operationalized in an initial implementation aimed at recreating the features of Version 1 while adding one some core functionality necessary for a fully functioning version; the goal is to have this available for the 2021 TTS. This section provides a brief overview of the state of TRAISI at the time of this report.

8.4.1 Survey and user management

TRAISI currently allows for multiple user groups, each having their own surveys. As a research and agency platform, all surveys while owned by individuals can only be created underneath a group.

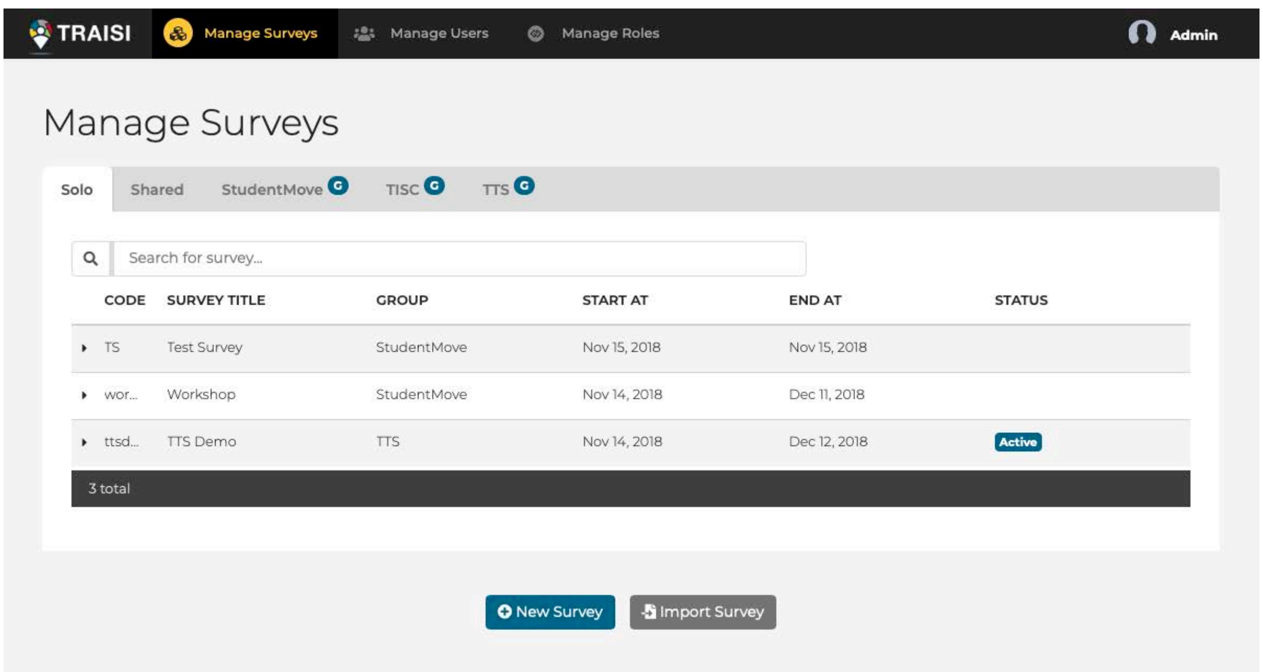

Figure 8-2 Surveys are owned by individuals and organized by group

8.4.2 Survey execution via codes or email

Survey execution can be done via individual or group codes, where group codes allow for a single code to be used multiple times, each time starting a new survey. Recruitment via emails and scheduling (for reminders) are planned.

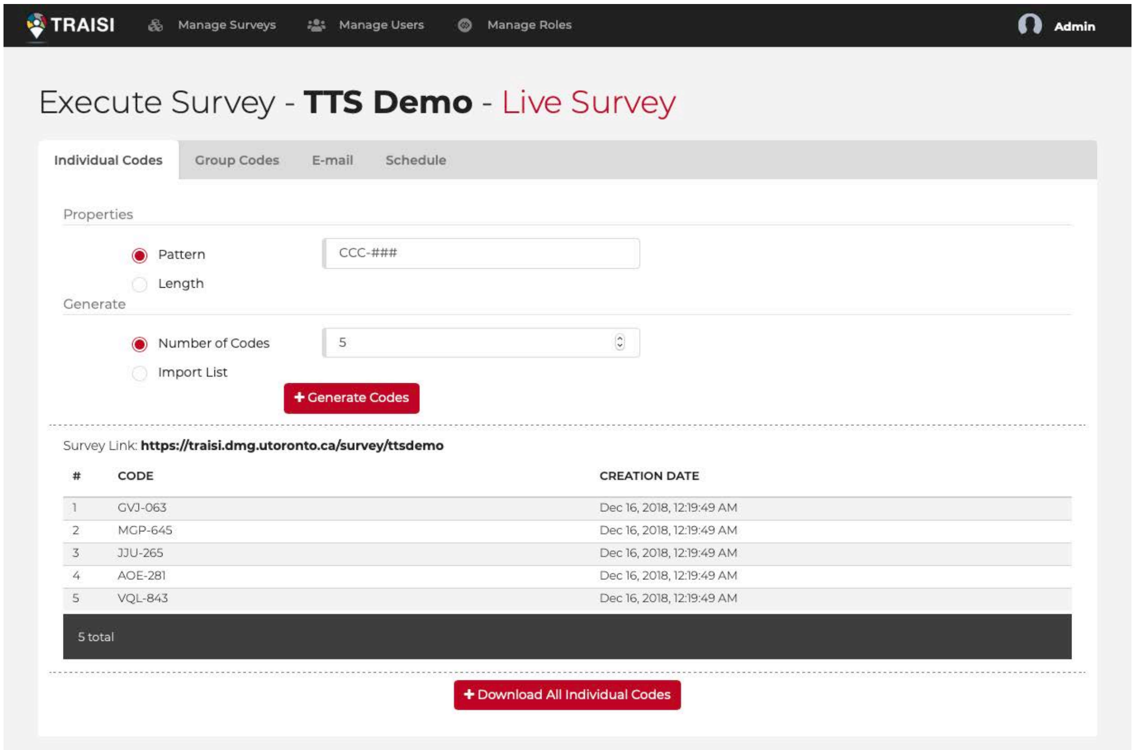

Figure 8-3 Surveys can be accessed using codes with patterns user-specified

8.4.3 Survey design

TRAISI's current implementation incorporates a survey designer allowing all survey pages to be designed using a drag-and-drop interface. This is available for both landing (Figure 8-4), privacy policy and thank-you pages, as well as survey question pages (Figure 8-5).

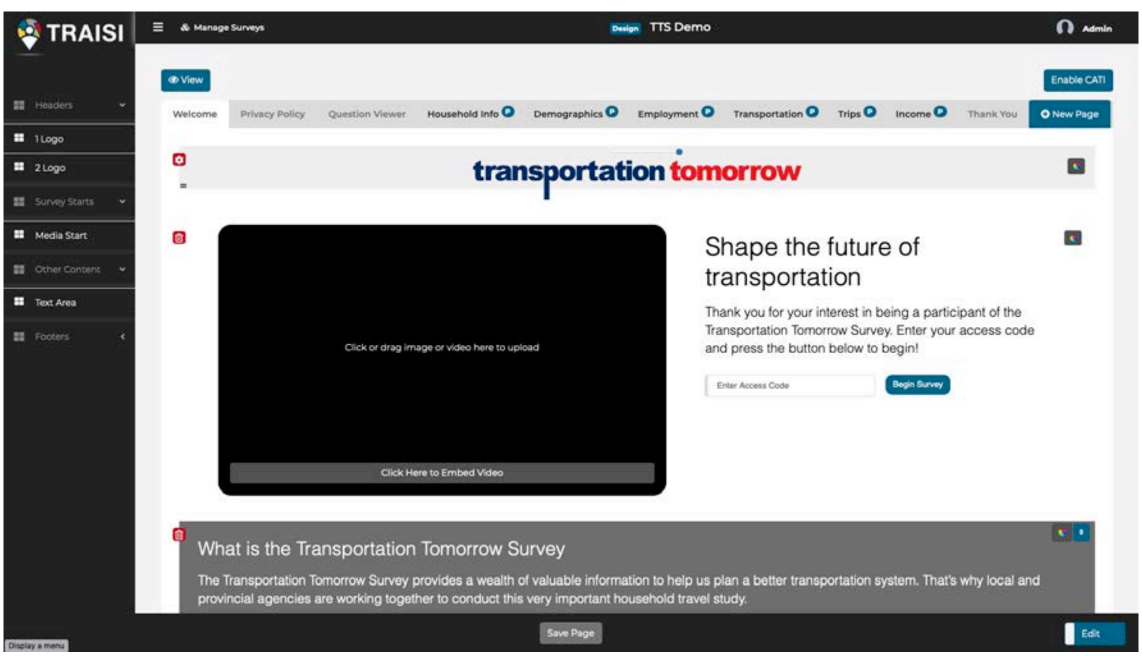

Figure 8-4 The TRAISI survey designer allows for landing pages to be designed

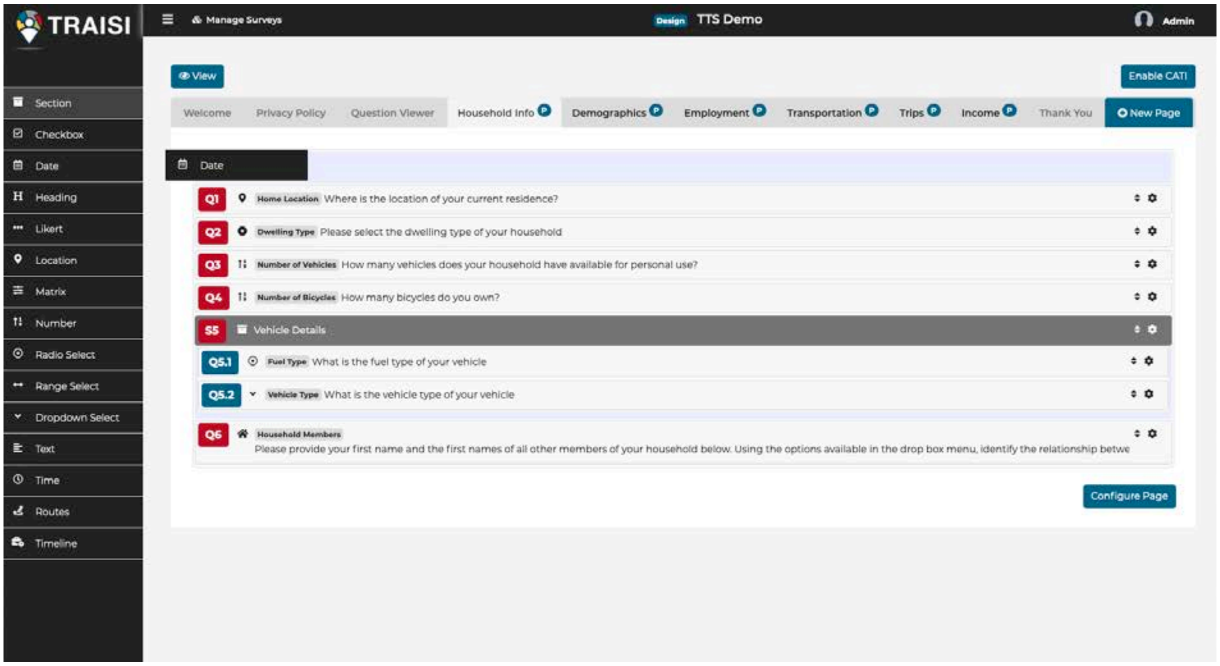

Figure 8-5 Survey page design is performed using a drag and drop interface

Questions are included as individual external modules specified using the TRAISI software development kit (SDK). The SDK allows each question to specify advanced configurations (beyond basic question text and optional flags). Complex conditionals are also available (for example, to set questions based on respondent residence (Figure 8-6)) and can target questions or even question options to be hidden. Other basic survey features (piping, repeats, etc.) are also implemented in the current version.

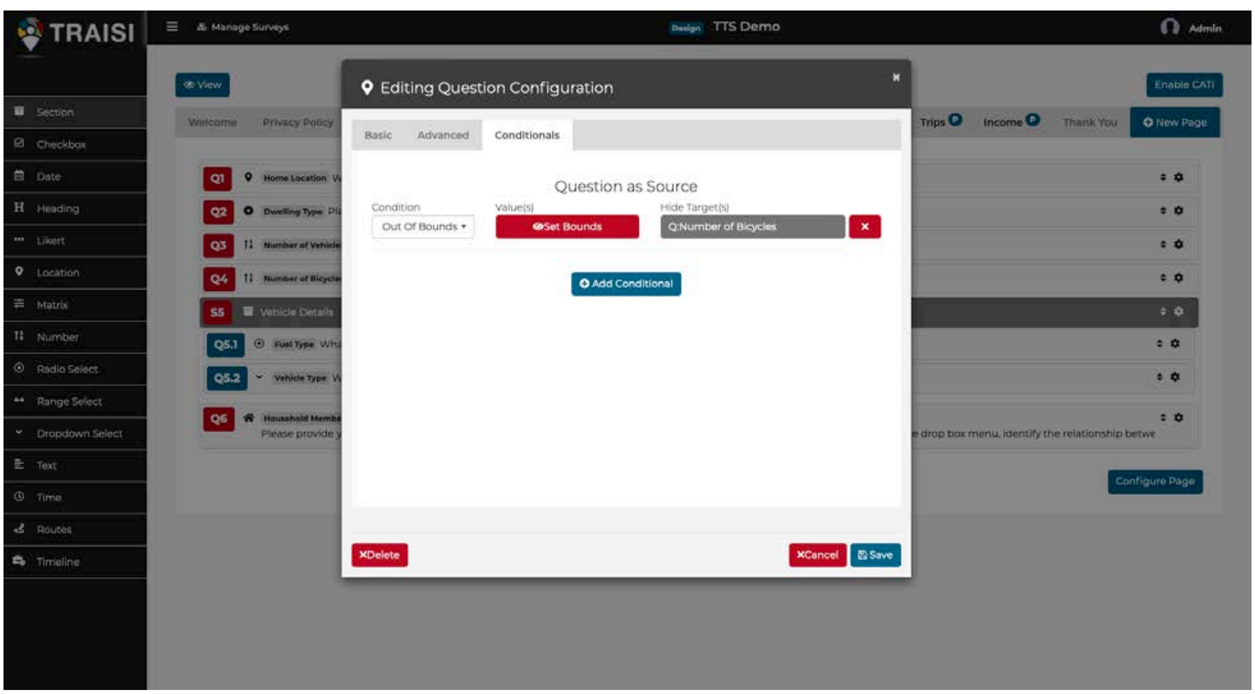

Figure 8-6 TRAISI allows for complex conditionals; here location conditionals can be set

8.4.4 Respondent interface

TRAISI's initial respondent interface allows for question-by-question displaying of surveys. Validation is presented immediately, with some questions allowing an auto-advance ability to reduce response time and mouse clicks. A progress header shows the current state of the respondent's survey. The two figures below show the interface while also illustrating the state of the trip diary interface with a redesigned timeline based on findings during field tests, and trip routes interface migrated from version 1 (Figure 8-8).

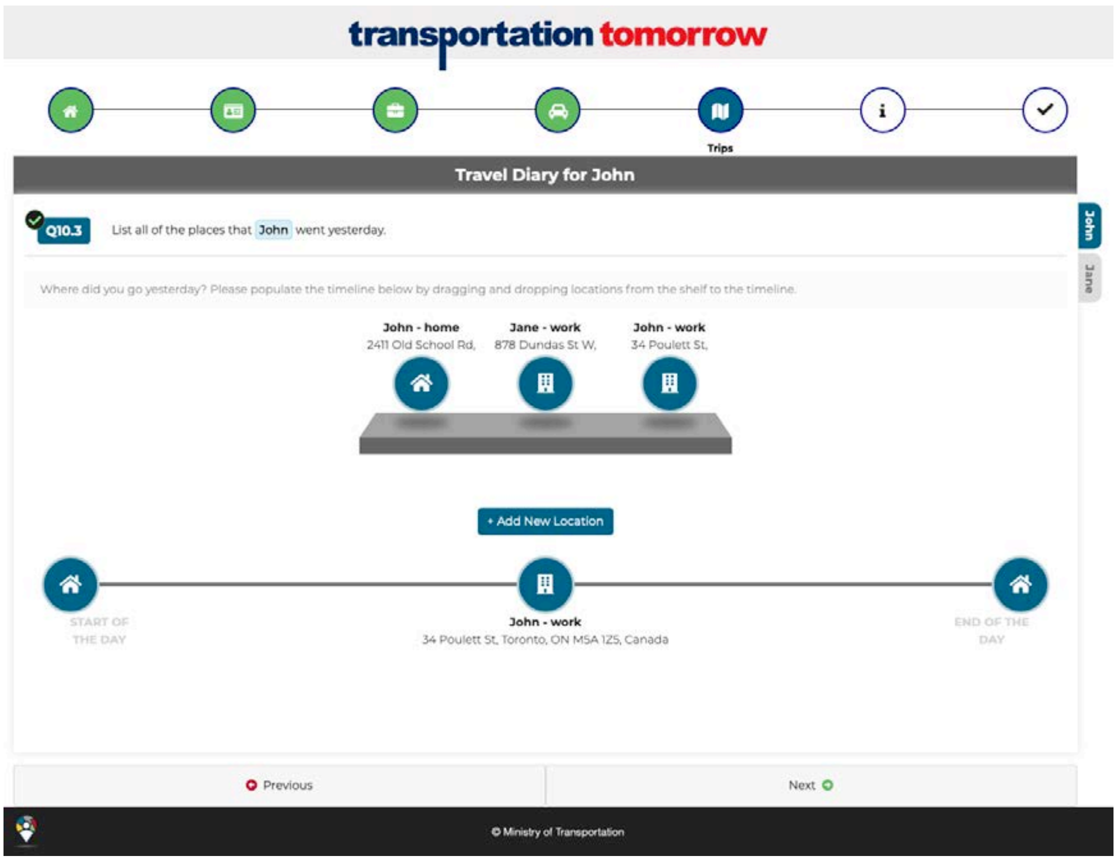

Figure 8-7 Survey respondent interface showing redesigned trip diary timeline

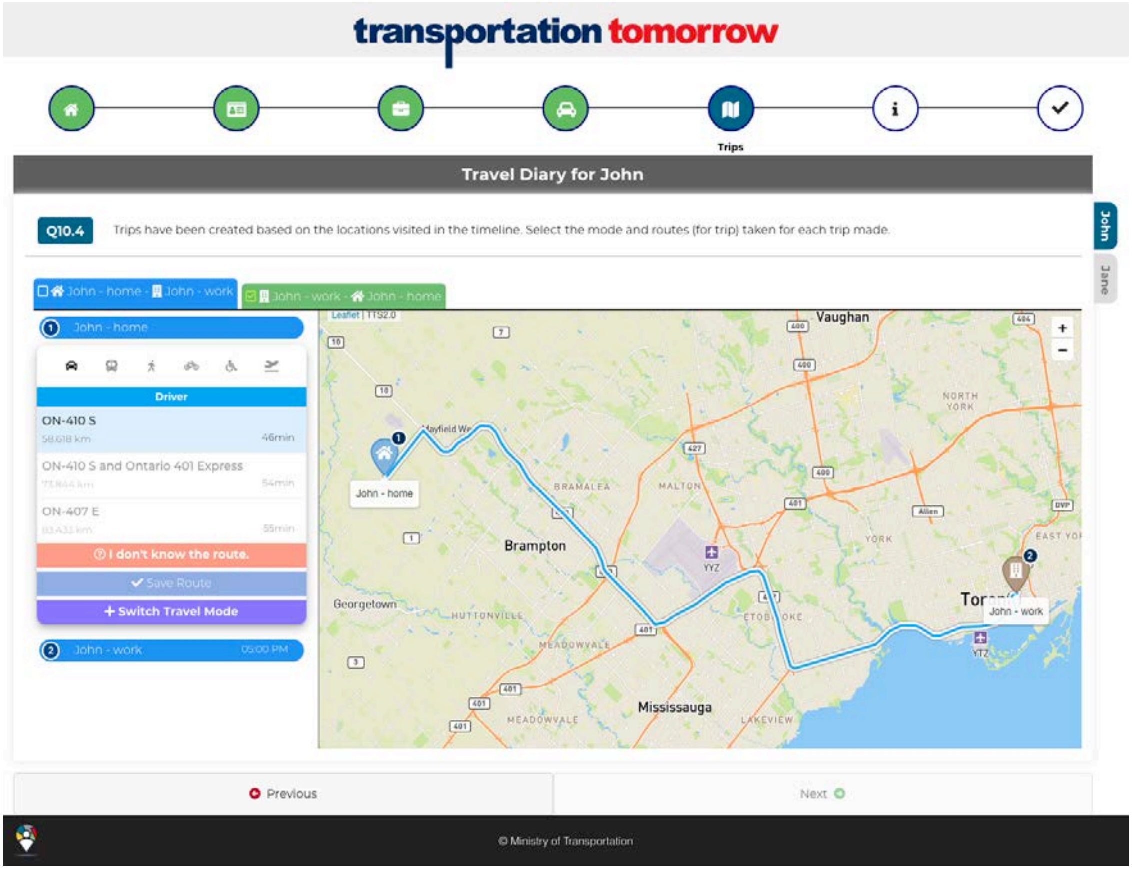

Figure 8-8 Survey respondent interface showing migrated trip diary routes interface

8.5 Roadmap for viability as a TTS platform

While significant progress has been made towards an implementation of TRAISI version 2, there remains work to be done to make the platform viable for the next TTS. The main stages (trip question improvements, CATI interface, monitoring and analysis, pilot testing) are provided in Figure 8-9. In advance of use in the next TTS, TRAISI is set to be field tested as the platform for the next StudentMoveTO post-secondary survey in fall of 2019.

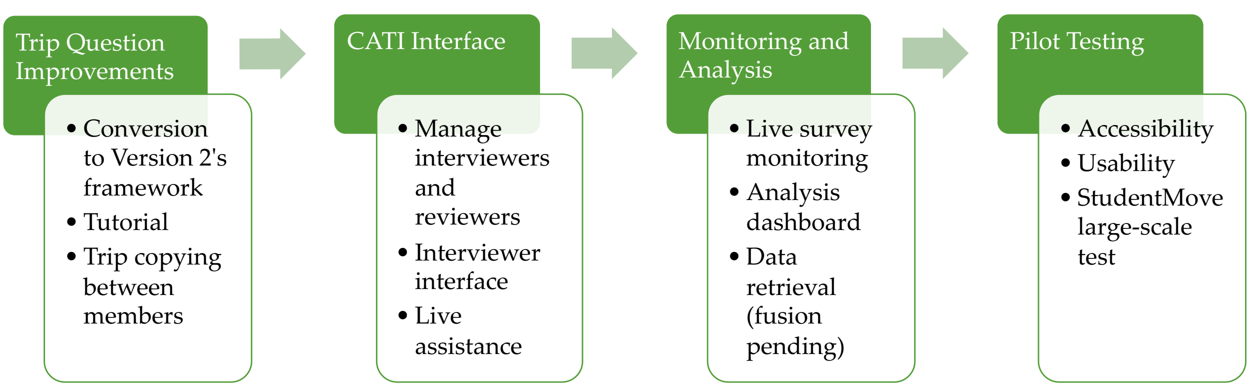

Figure 8-9 TRAISI roadmap towards the 2021 TTS

9 2021 TTS RECOMMENDATIONS AND FUTURE DIRECTIONS

9.1 2021 TTS Recommendations

This section provides consolidated recommendations for the 2021 TTS based on the findings of the TTS 2.0 project presented throughout this report. Aspects touched on include the specific recommended surveys to be conducted as part of the core-satellite structure, and how to conduct the core TTS surveys. The latter include modifications to the current questionnaire, and guidance on sample frame construction, sampling method, size and survey mode. Brief justifications are provided with extended rationales provided via links to relevant sections in the report.

9.1.1 Recommended Core-Satellite Data Collection Structure

Figure 9-1 provides a schematic of the core-satellite structure recommended for the 2021 TTS. It is based on the best available information collected in the course of the project about the surveys necessary to collect a representative set of travel demand data, and judgements made about the probable state of new data sources and methods at the time of the next TTS.

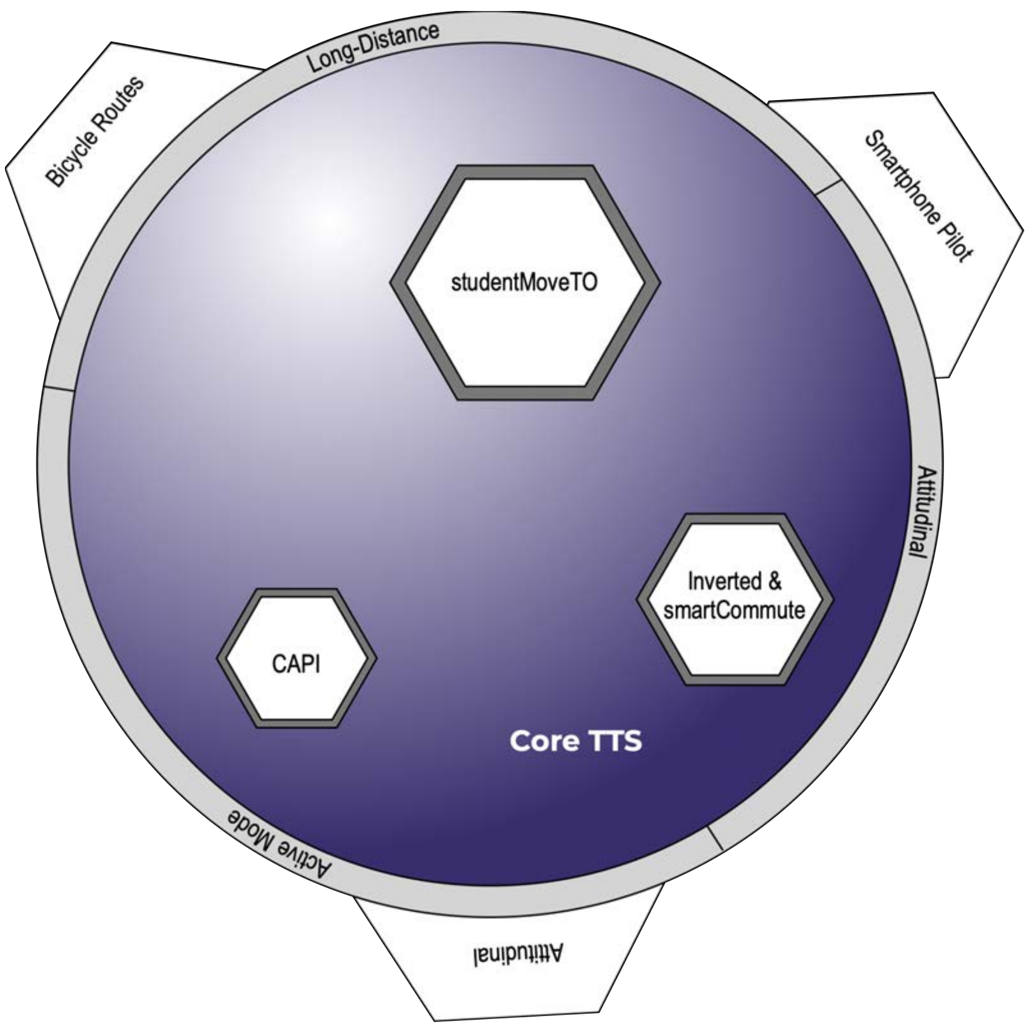

Figure 9-1 Recommended implementation of the core-satellite data collection structure for the 2021 TTS

Core Survey: A modified version of the TTS remains the core survey in this framework, with acknowledgements made that it is unlikely to be representative given issues detailed with household-based survey methods. Similar to the makeup of the 2016 TTS, the core survey is multi-frame and multi-mode, with details on execution provided here [**Final, 9.1.3-9.1.5**]. Issues with newer methods using newer technology need to be addressed before widespread use. As a result of this, and to minimize disruption and maximize comparability, recommendations focus on execution.

Core-extension Surveys: Core extension surveys [**Final, 3.3.2**] allow for additional data to be collected at a population level and are conducted via attachment to the end of the core survey for a random sample of respondents. With the multi-municipality composition of the TTS region, while uniformity would be ideal, these additional surveys can be set at a local level to conform to the specific needs of each municipality. Recommended surveys are those dealing with active modes (collecting additional information on bicycling and walking), attitudinal (which could include a stated preference survey to test potential infrastructure changes), and long-distance travel.

Core-filling Surveys: Core-filling surveys [**Final, 3.3.3**] mimic the core survey, while targeting specific groups under-represented in the TTS.

Three core-filling surveys are recommended for the 2021 TTS:

- College survey piggybacking on the recently established and expanding StudentMoveTO
- In-person (CAPI) surveying of specific geographies where gaps are observed
- Employment-vector recruiting (inverted) using a mix of partnership with SmartCommute and independent surveying of medium-sized businesses using on-premise personnel

The first of these (StudentMoveTO) is recommended as an integral part of TTS data collection, with under-representation of students known to be an ongoing issue with the TTS, particularly for those living on campus. While StudentMoveTO has been established, it is currently a Toronto focused effort, with the city's 4 universities on board, with colleges being included for the 2019 iteration. As a result, incorporation of StudentMoveTO will require expansion of the survey to post-secondary institutions across the GGHA region. Negotiation is also needed to bring the questionnaire in line with the TTS, while allowing for additional questions important to specific institutions.

On the other hand, for the latter two core-filling surveys, their use is dependent on an initial analysis of TTS results to identify gaps that would require supplemental and alternative efforts that go beyond merely increasing sample attempts in a region. As a result, these would be best held either in the following spring or subsequent fall period and conducted on an as-needed basis.

Linked Satellites: Linked satellites [**Final, 3.4.1**] provide a means to collect additional travel demand data about specific populations, segmented in various ways (demographics, modes used, etc.). As with the core-extension surveys, while recommended to be decided upon collectively, they can be set at a municipal level, providing the means to conduct existing surveys in coordination with the TTS to produce compatible data. Three linked satellites are recommended:

- Biking routes survey: collection of trips (to the level of paths taken) of frequent bicycle users over a longer period of time (e.g. week or two); this would necessitate the use of a partly passive method of collection such as a smartphone app
- Attitudinal surveys: stated preference surveys that collect data on attitudes towards on hypothetical scenarios but for specific population groups
- Smartphone pilot survey: smartphones are not yet at a state where they would representatively survey the population, and have issues remaining in identifying trip purposes and modes; this

survey will act as a pilot to gauge their readiness for large-scale deployment as part of the core survey; if representativeness issues remain (as experienced in the TTS 2.0 City Logger field test), it could act as a supplement to the core data. For an example of how to conduct a smartphone survey see [**2017 City Logger**], which used two common industry apps. In 2021, participants for a smartphone survey could be recruited via a download link to an app store and unique code to enter at the end of the core or core-extension survey.

Independent Satellites: Independent satellites [**Final 3.4.2**] are those that were conducted within a geographic region of the TTS, but independent of the core TTS sampling. Beyond the considerations in Section 3.4.2 to take when conducting an independent satellite, apart from a recommendation to utilize the TRAISI platform to ensure more compatible data are produced and stored alongside TTS data, no additional guidance/recommendations are provided in this report. The needs of individual municipalities will determine these additional satellites.

Passive Data: With the current state of available passive data [**Final, 3.4.3, 7.3**], concrete recommendations on the use of passive data are not currently possible. While there is great potential, as detailed in these sections, in using passive data for a variety of purposes, most available sources in the TTS region are not yet matured. As a result, the level to which their potential will be realized and the mechanisms to fuse their data with those from the TTS is unclear; recommendations are therefore premature at this point.

For example, PRESTO has yet to be fully implemented in the region leading to uneven penetration, with the current older implementation not yet at a stage where reliable travel demand data could be extracted. Implementation issues include lack of GPS location, minute instead of second-based timestamps and an abundance of unlinked (one-way trips) that prevent determination of destination given the tap-on only systems used by most agencies. This might change with proposed plans, namely full PRESTO fare media to allow for complete penetration, GPS-enabled devices and postal code FSA becoming available for registered users. An ideal implementation would also ensure that GTFS schedule information is imported into the PRESTO system to attach relevant route, trip and vehicle identifiers, necessary to delineate between close stops during any AVL/PRESTO fusion process. Up-to-date inventory of device identifiers matched to location (both vehicle and station entrances) would also assist in this fusion step to improve the accuracy of generated OD matrices.

The potential of cellphone data, which was not available for study during the course of TTS 2.0, is also unclear, with known issues in accuracy, mode detection and lack of available demographics needing further study to understand its place.

9.1.2 Final Questionnaire Recommendations

To allow for comparability between subsequent years, recommendations for the 2021 TTS questionnaire have been focused into 3 key areas:

- Adjustments of certain response option categories to bring them in line with standards in other areas (particularly Statistics Canada)
- Expansion of response options to provide sufficient detail for travel demand modelling
- Additional questions to collect data necessary for modern travel demand and household interaction models

9.1.2.1 MODIFICATIONS AND EXPANSION OF RESPONSE OPTIONS

Income

Description Household's total income last year from all sources before income tax

Rationale for Modification Better match 2016 Census categories and add greater granulation under $40K and over $125K to account for inflation of incomes since the start of TTS.

Current Options	Recommended Options
$0 to $14,999	$0 to $14,999
$15,000 to $39,999	$15,000 to $30,000
	$30,000 to $39,999
$40,000 to $59,999	$40,000 to $49,999
	$50,000 to $59,999
$60,000 to $99,999	$60,000 to $69,999
	$70,000 to $79,999
	$80,000 to $89,999
	$90,000 to $99,999
$100,000 to $124,999	$100,000 to $124,999
$125,000 and above	$125,000 to $149,999
	$150,000 to $199,999
	$200,000 and above
Decline/ don't know	Decline/ don't know

Recommendations for additional questions are made following trials made during the TTS 2.0 field tests to ensure that they were viable and did not lead to excessive burden and affect completion rates.

Sex

Description Gender of the person

Rationale for Modification Gender sensitivity

Current Options	Recommended Options
Female	Female
Male	Male
	Other: [textbox]
Unknown	Unknown (CATI)/Prefer Not to Answer (CAWI)

Occupation

Description Person's occupation type

Rationale for Modification Match categories used by Statistics Canada (NOC 2016) and improve clarity. Note that these categories should come with help text to provide descriptions/examples for web respondents.

Current Options	Recommended Options
Professional/Management/Technical	Professional
	Management
	Technical and Paraprofessional
General Office/Clerical	Administration and administrative support
Retail Sales and Services	Sales
	Personal or customer information service
Manufacturing/Construction/Trades	Industrial, construction or equipment operation trade
	Worker or labourer in transport and construction
	Natural resources, agriculture and related production occupation
Not Employed	Not Employed
Unknown	Other

Trip Purpose

Description Purpose of origin and destination for each trip

Rationale for Modification Increased granulation of categories to provide additional data for activity-based models. Improvements in trip rates by helping to remind respondents of specific activities that might have otherwise been omitted.

Current Options	Recommended Options
Home	Home
Work	Usual Work Place
	Work-related / Business meeting
School	School / Education
	School-related / School trip
Marketing/Shopping	Shopping and errands (groceries, mall, gas station, etc.)
Other	Restaurant, bar, coffee
	Visiting friends, family
	Recreation, sports, leisure, arts
	Worship, religion
	Services (bank, haircut, mechanic, etc.)
	Health and personal care
Facilitate passenger	Drop someone off
	Pick someone up
Daycare	Daycare
Unknown	Unknown

Trip Diary Collection Minimum Age

Description Minimum age to collect trip information (all respondents)

Rationale for Modification Bring collection of trip data into line with other Canadian surveys and acknowledgement that younger individuals do travel alone (particularly with free transit access).

Current Minimum Age	Recommended Minimum Age
10 years old	6 years old

9.1.2.2 RECOMMENDED ADDITIONAL QUESTIONS

Housing Tenure

Description Whether residence is owned or being rented

Rationale and Justification for Options Measure of permanence and consistency of travel behaviour.

Options Owner or renter

Residence Duration

Description Length of current residency

Rationale and Justification for Options Measure of reliability and consistency of travel behaviour.

Options Fill in.

Vehicle Information

Description Data on vehicles owned by household members

Rationale Use for vehicle ownership and emissions modelling, but primarily to allow for vehicle used to be selected for trip diaries to collect information on household interactions

Options (adapted from the US National Household Travel Survey)

Vehicle type	Automobile/ Car/ Station Wagon
	Cargo or Passenger Van
	SUV or Minivan
	Pickup Truck
	Other Truck
	Motorcycle/Motorbike
	Recreational Vehicle (RV)
	I don't know/ unknown
Vehicle fuel type	Gas
	Diesel
	Hybrid or alternative fuel
	Electric
	Other fuel
	I don't know/ unknown
Vehicle model year	Fill in.

Carshare Membership

Description Whether person/household has a carshare membership

Rationale With shift towards transportation as a service, provides an important input (lack of or restrictive number of owned vehicles may not indicate lack of driving), as a supplement to transit pass ownership question.

Kinship

Description Relationship of household members during listing

Rationale Provides household structure important for understanding interactions and provides indication of non-traditional arrangements

Options (adapted from US NHTS)

Spouse/Partner
Child
Parent
Grandparent
Grandchild
Roommate
Other

Accompanying household members and vehicle usage on trips

Description Any household members accompanying a respondent on their trips and indication of vehicle used

Rationale Collect household interaction data currently omitted from the TTS, where these have to be inferred from trip times and locations; allow for auto-copying of trips between household members

Note With a web-based interface (CATI and CAWI) these options will be auto filled based on prior answers

9.1.3 Sampling Frames

A full analysis of sample frames is presented in [**Final, 3.1**]. Based on that analysis, the following recommendations can be made for the various survey components of the 2021 TTS core-satellite framework.

9.1.3.1 CORE AND CORE-EXTENSION SURVEYS

Owing to the decreasing comprehensiveness of the landline frame, the core of the 2021 TTS should adopt an address-based multi-frame sampling approach. The frames used should comprise of address & phone (landline), address-only and phone-only frames similar to the 2016 TTS. The landline frame remains the most cost-effective approach given its high completion rates (deriving from the ability to directly contact individuals and follow-up), but its demographic bias leaves it no longer sufficient as a sole source frame. While the mail frame has been shown to be representative, work remains, however, work to be done with respect to its recruitment and follow-up process that to-date has resulted in significantly lower response rates. The phone-only sample frame can be derived from RDD and verified cell phone listings. It is important to include this frame in the core survey since the socio-demographics and trip patterns of CPO households are different from the general population. Further research, however, is needed given the low response rates found during its initial use in the 2016 TTS. As, this may be as a result of the methods employed, efforts should focus on ways to improve execution such as advanced SMS texting. Volunteering/open frames are a possibility but would be best served as a registration mechanism, possibly for satellite surveys given the intrinsic self-selection bias present in the act of volunteering. In particular, those who volunteer would likely have inflated trip rates leading to biased result.

Core extension surveys [**Final, 3.3.2**] should use the same sample frame as that of the core. This may be considered as a panel-based frame, where the respondents for the core extension survey are sampled directly from the core sample.

9.1.3.2 CORE-FILLING SATELLITE SURVEYS

On the other hand, core-filling satellite surveys should be based on an address-based frame or company/institutional frame depending on their end goal. An address-based frame would be preferred if the aim of the core-filling survey is to reduce geographical gaps, whereas company/institutional frames would be ideal for reducing demographic gaps. For example, StudentMoveTO can be used for improving the representation of student-aged respondents (particularly those living on campus) and the inverted frame can be used to target specific businesses with underrepresented demographics, or underrepresented geographic areas.

9.1.3.3 OTHER SATELLITES

In terms of the other satellites, linked satellites should use panel-based frames constructed from the core sample, similar to the core extension survey. They, however, differ from core-extension by targeting a specific sub-population of the core. As for the independent satellites, frame selection would vary depending on the survey purpose.

9.1.4 Sampling Method and Size

The recommended sampling method varies based on the frame and type of survey. A review of sampling methods (both spatially and temporally) is presented in [**Final, 4.2**]. Based on the critical review of different sampling methods, recommendations are made, and re-iterated below, for the different components of the 2021 TTS:

- For the core survey, geographically stratified random sampling technique should be adopted.
- Respondents for the core-extension survey should be sampled from the core sample according to a predefined sampling rate using the simple stratified sampling method.
- For core-filling surveys, disproportionate stratified sampling may be appropriate.
- Linked satellites should randomly sample potential respondents who belong to the targeted group using the list of individuals who showed interest to participate in future surveys.
- Depending on the type of population to be surveyed, a choice-based sampling method may be more appropriate for independent satellite surveys, such as active mode or transit on-board surveys.

For the core survey, it would be best to retain the current repeated cross-sectional nature rather than shifting to continuous data collection owing to the following reasons:

- A shift from cross-sectional to continuous surveys with the current sample size will result in lower data quality.
- The sample size to support the shift would be too large to be practical.
- Leveraging available and emerging passive data sources with appropriate fusion techniques would instead allow for capturing changes in travel patterns while maintaining data quality.

Approaches to calculate an appropriate sample size, particularly for a core HTS, is presented in [**Final, 4.3**]. Based on review of sample sizes used in other HTS, statistical tests to achieve desired confidence intervals and margins of error, and a case study of the 2011 TTS, led to the following recommendations for the core TTS surveys.

For the core survey, the current sample size of 5% of the population is recommended. Even though shifting to a stratified random sample of 4% with additional augment samples for individual regions/cities may be helpful to gather sufficient data from hard-to-reach or low-population zones, it may cause administrative difficulty when conducting the overall core survey. Rather, the core-filling survey is designed within the core-satellite approach to overcome this problem. As the core-filling surveys generally employ cluster sampling (with full-institution email-outs), setting sample size is less of a concern than the method to fuse their data with those of the core survey.

Since the core-extension survey will randomly sample from the core sample, its sample size will be fraction of the overall core sample. The exact sample size of this survey will be determined by the specific travel data to be collected and its application. This will dictate the sample size required to adequately capture the specific travel behavior.

9.1.5 Recruitment Methods and Incentives

A summary of the TTS 2.0 findings surrounding recruitment methods and incentives are presented in [**Final, 4.4**]. While details on execution are found in that section, the consolidated recommendations are re-iterated below.

For the multi-frame core survey of 2021 TTS, households from the landline and address-based frames should be recruited through advanced/pre-notification letter, whereas the cell phone-based sample is recruited through advanced texting. Respondents for the core-extension survey should be introduced to the survey immediately after the completion of the core questions based on random selection, alleviating the need for specific recruitment. For the core-filling satellite survey, recruitment can be done using the email list available with the institution; on-site recruitment (e.g. call-centre reps reassigned to company lobbies) can also be helpful in this regard. On the other hand, for the linked satellites, recruitment should be done using the email or phone list of core respondents who showed interest to participate in future surveys. Finally, the recruitment method for the independent survey will depend on the end goal of the survey. In addition to these methods, the independent survey can adopt innovative and emerging recruitment techniques like roadside intercept and crowdsourcing, given that a proper data fusion technique is applied to integrate the collected data with the core.

Incentives should be avoided in the core survey, as it may cause self-selection bias in the sample, making comparability difficult with prior TTS. They can, however, be considered for satellite surveys where respondent burden is considerably high, or in specific core-filling surveys to encourage participation in groups that have been shown to be difficult to attract (e.g. students). Incentives may also be appropriate for core-extension surveys depending on their length and added burden.

9.1.6 Survey Modes

A critique on the various survey modes possible for travel surveys (CATI, CAWI, CAPI and smartphone) are presented in [**Final, 5**]. While each individual mode has both strengths and weaknesses, analysis of both the literature and field test results have made clear that a single survey mode is not sufficient for large-scale travel surveys like the TTS. The multi-frame approach inherent to the core-satellite framework and varying preferences of modes within and between populations have made it a necessity to conduct the survey over multiple modes. Ideally, respondents should also be provided with the choice of their preferred mode of response and be able to seamlessly switch between modes. This does, however, present challenges to harmonize biases present in each mode, while maintaining consistent terminology between various surveys.

For the core 2021 TTS, two main modes are recommended (CATI and CAWI). These two modes cover feasible response modes for all household-based frames of the core survey. CAPI is also an option if in-person supplemental surveys are deemed necessary to fill geographic gaps based on results of the initial core survey. These 3 modes are compatible to allow for a multi-mode approach not only for the core survey but core-extension and core-filling surveys, and both linked and independent satellites. As described in [**Final 8.1**], to harmonize biases and maximize semantic compatibility, both within the same core survey and between different surveys of the framework, a common platform would be recommended. This would have an added benefit of facilitating data fusion of information collected across the modes.

Smartphone-based collection is not, however, recommended for the core survey at this time, with passive multi-day data collection not yet ready for widespread use, for a variety of technical and population representation issues. Smartphone-based multi-day collection does have its place in smaller linked or independent satellites, for focussed studies on multi-day travel where detailed route traces are desired.

9.2 Future trends in survey design and the future of TTS research

The recommendations in this report, while a strong departure from the 2011 TTS, are relatively conservative compared to the 2016 TTS where significant methodological changes were made to run the survey using multiple frames and modes. The recommendations build on these changes, aiming to both refine them by providing guidance to improve execution, and place this multi-pronged methodology within a formal survey collection architecture. This architecture is future-facing given the clear pattern emerging that a core TTS survey will be progressively less complete and require additional surveys to feed data-heavy modelling methods.

In part, this conservative approach is meant to ensure that data from subsequent TTS can be comparable, while allowing for flexibility of approach and collection. This is necessary to both make up for any data or coverage deficiencies as well as allow for testing and incorporating emerging data sources. It is also important given uncertainties in the state of passive data and smartphone technology. While the trend of travel demand data collection towards these emerging sources is clear, significant changes are likely to occur in the not-so-distant future that hamper their inclusion in the 2021 TTS. The recommended core-satellite structure enables this type of exploration through the use of linked or independent satellites that have the flexibility to experiment with methods.

There are some key trends worth highlighting that are expected for future TTS. First are the continued expansion and availability of passive data sources for continuous observation and measurement of travel demand. Of particular note are data acquired from the PRESTO transit smart card and cell phone towers. There is a potential to eventually move to the use of these sources for OD trip matrices for updating matrices between survey years or even as a full replacement with a smaller focussed set of TTS surveys collecting data to allow for demographic and behavioural analysis. Whether this potential is realized, however, is heavily dependent on penetration rates, device upgrades to provide required data and the ability of researchers to solve some fundamental technical issues described earlier in this report. Next, survey modes are expected to continue to evolve as call-based methods become progressively more difficult to execute, resulting in a shift towards web and smartphone methods. This is dependent on smartphone apps continuing to improve (both technically and in their acceptance by the public), and the development of TRAISI to improve CAWI methods and integrate data from all modes. Finally, handling data from these many sources will require a shift in the data management model currently used for TTS (handled by the Data Management Group at the University of Toronto) from purely data collection/management to also providing standardized integration of modelling methods for non-academic end-users. This will be required for proper application of data fusion techniques to eventually allow for accurate synthetic populations to be generated that take into account all input sources simultaneously.

While significant work was performed across many areas within travel demand data collection in the course of the TTS 2.0 project, given the trends described, a continuous research effort is needed to progressively evolve the TTS over time. Part of this effort should be to deal with how to exploit and integrate data sources from emerging technologies, particularly methods of data fusion. Also critical, but outside the scope of the TTS 2.0 project, are improvements to methods to recruit and encourage participation; while predominantly a marketing task, it is critical to convince the public of the importance of the TTS to improve response and completion rates, as well as data quality.

10 REFERENCES

Albaum, G. et al., 2010. Designing Web Surveys in Marketing Research: Does Use of Forced Answering Affect Completion Rates?. *The Journal of Marketing Theory and Practice,* pp. 285 - 294.

Alsger, A. et al., 2018. Public transport trip purpose inference using smart card fare data. *Transportation Research Part C: Emerging Technologies,* Volume 87, pp. 123-137.

Alta Planning + Design, 2015. *City of San Diego Pedestrian Master Plan,* San Diego: Alta Planning + Design.

Armoogum et al., J., 2014. *Survey Harmonization with New Technologies Improvement (SHANTI),* Champs-sur-Marne: Recherches.

Badoe, D. A. & Steuart, G. N., 2002. Impact of interviewing by proxy in travel survey conducted by telephone. *Journal of Advanced Transportation,* pp. 43 - 62.

Barry, J., Newhouser, R., Rahbee, A. & Sayeda, S., 2002. Origin and destination estimation in New York City with automated fare system data. *Transportation Research Record: Journal of the Transportation Research Board,* Volume 1817, pp. 183-187.

Bayart, C., Bonnel, P. & Morency, C., 2009. Survey mode integration and data fusion: methods and challenges. In: *Transport survey methods: Keeping up with a changing world.* s.l.:Emerald Group Publishing Limited, pp. 587-611.

Beckman, R. J., Baggerly, K. A. & McKay, M. D., 1996. Creating synthetic baseline populations. *Transportation Research Part A: Policy and Practice,* 30(6), pp. 415-429.

Bierlaire, M., Chen, J. & Newman, J., 2010. *Modeling route choice behavior from smartphone GPS data,* Switzerland: Ecole Polytechnique Federale de Lausanne.

Bose, J. & Giesbrecht, L., 2004. Patterns of proxy usage in the 2001 National Household Travel Survey. *ASA: Survey Research Methods, Bureau of Transportation Statistics.*

Center TRT, 2013. *Nashville Area Metropolitan Planning Organization Active Transportation Funding Policy.* [Online]
Available at:
http://www.centertrt.org/content/docs/Intervention_Documents/Intervention_Materials/Nashville_MPO/Survey_Questions_-_Bike_Ped_Study.pdf

Correia, G. & Bradley, M., 2010. *Chapter 21 Stated-Preference Surveys.* [Online]
Available at: http://www.travelsurveymanual.org/Chapter-21.html

Couper, M., Baker, R. & Mechling, J., 2011. Placement and Design of Navigation. *Survey Practice.*

Cunha-e-Sa, M. M. L., Nunes, L. & Otrachshenko, V., 2012. Protesting and Justifying – A Latent Class Model for Contingent Valuation with Attitudinal Data. *Environmental Resource Economics,* pp. 531 - 548.

Dal Grande, E., Chittlebrough, C. R. & Campostrini, S., 2016. Pre-Survey Text Messages (SMS) Improve Participation Rate in an Australian Mobile Telephone Survey: An Experimental Study.. *PloS one ,* 11(2).

D'Ambrosio, A., Aria, M. & Siciliano, R., 2007. *Robust tree-based incremental imputation method for data fusion.* Berlin, Heidelberg, Springer, pp. 174-183.

De Bruijne, M. & Wijnant, A., 2013. Comparing survey results obtained via mobile devices and computers: An experiment with a mobile web survey on a heterogeneous group of mobile devices versus a computer-assisted web survey.Comparing survey results obtained via mobile devices and computers. *Social Science Computer Review,* pp. 482 - 504.

D'Ambrosio, A., Aria, M. & Siciliano, R., 2007. Robust Tree-Based Incremental Imputation Method for Data Fusion. *IDA,* pp. 174-183.

D'Orazio, M., 2013. [Online]
Available at: http://en.eustat.eus/productosServicios/datos/Seminario_55_Slides.pdf

D'Orazio, M., Di Zio, M. & Scanu, M., 2006. *Statistical Matching: Theory and Practice*. s.l.:John Wiley & Sons.

Edwards, S., Ivey, S., Lipinski, M. & Golias, M., 2012. Bicycle and Pedestrian Studies Based on Data from National Household Travel Survey. *Journal of the Transportation Research Board,* p. 150–156.

Endemann, P., Kockelman, K. & Wilder, C., 2010. *Chapter 1 Introduction*. [Online]
Available at: http://www.travelsurveymanual.org/Chapter-1-1.html

Everett, J., Ruegg, S. & Tardiff, R., 2014. *Chapter 15 Vehicle Intercept and External Station Surveys*. [Online]
Available at: http://www.travelsurveymanual.org/Chapter-15-2.html

Fellegi, I. & Sunter, A., 1969. A theory for record linkage. *Journal of the American Statistical Association,* 64(328), p. 1183–1210.

Gilula, Z., McCulloch, R. E. & Rossi, P. E., 2006. A direct approach to data fusion. *Journal of Marketing Research,* 43(1), pp. 73-83.

Goulias, K. G., Pendyala, R. M. & Bhat, C. R., 2011. *Total Design Data Needs for New Generation Large Scale Activity Microsimulation Models,* s.l.: s.n.

Hassounah, M., Cheah, L. & Steuart, G., 1993. Underreporting of trips in telephone interview travel surveys. *Transportation Research Record,* pp. 90 - 94.

Hood, J., Sall, E. & Charlton, B., 2011. A GPS-based bicycle route choice model for San Francisco, California. *Transportation letters,* 3(1), pp. 63-75.

Jin, X., Hossan, S., Asgari, H. & Shams, K., 2018. Incorporating Attitudinal Aspects in Roadway Pricing Analysis. *Transport Polcy,* pp. 38 - 47.

Jue, A. & Luck, K., 2014. *Update: Participation of mobile users in online surveys.*. [Online]
Available at: www. decipherinc. com/n/uploads/images/pages/Decipher_Mobile_Research_White_Paper_Update. pdf

Kiesl, H. & Rässler, S., 2006. *How valid can data fusion be?*. [Online]
Available at: http://doku.iab.de/discussionpapers/2006/dp1506.pdf
[Accessed 25 July 2017].

Leulescu, A. & Agafitei, M., 2013. *Statistical matching: a model based approach for data integration,* s.l.: Eurostat European Commission.

Li, Z., Wang, W., Yang, C. & Ragland, D., 2013. Bicycle Commuting Market Analysis Using Attitudinal Market Segmentation Approach. *Transportation Research PArt A,* pp. 56 - 68.

Lohr, S., 2011. Alternative survey sample designs: Sampling with multiple overlapping frames. *Survey Methodology,* 37(2), p. 197–213.

Mamun, M., Yin, Y. & Srinivasan, S., 2010. *Trip Generation Characteristics of Special Generators,* Gainesville: University of Florida Transportation Research Center.

Munoz, B., Monzon, A. & Daziano, R., 2016. The Increasing Role of Latent Variables in Modelling Bicycle Mode Choice. *Transport Reviews,* pp. 737 - 771.

Nah, F., 2004. A Study on Tolerable Waiting Time: How Long Are Web Users Willing to Wait?. *Behaviour & Information Technology,* pp. 153 - 163.

Namazi-Rad, M. et al., 2017. An unconstrained statistical matching algorithm for combining individual and household level geo-specific census and survey data. *Computers, Environment and Urban Systems,* Volume 63, pp. 3-14.

National Academies of Sciences, Engineering, and Medicine, 2017. *Federal Statistics, Multiple Data Sources, and Privacy Protection: Next Steps,* Washington, DC: The National Academies Press.

Ohnmacht, T., Rebmann, K. & Brugger, A., 2012. *Swiss Microcensus on Mobility and Transport 2010.* Monte Varita: STRC 2012.

Prichard, D. R. & Miller, E. J., 2011. Advances in population synthesis: fitting many attributes per agent and fitting to household and person margins simultanrously. *Transportation,* Volume 39, pp. 685-704.

R.A. Malatest and Associates Ltd., 2018. *Design and Conduct of the Survey,* Toronto: R.A. Malatest and Associates.

Richardson, A., 2005. *Proxy Responses in Self-Completion Travel Diary Surveys,* Washington: The Urban Transport Institute for Reliable Urban Transportation Information.

Rodgers, W. L., 1984. An evaluation of statistical matching. *Journal of Business & Economic Statistics,* 2(1), pp. 91-102.

Rousseau, G., Mirzaei, A., Bonnel, P. & Cervenka, K., 2011. *Chapter 16 Transit Onboard Surveys.* [Online] Available at: http://www.travelsurveymanual.org/Chapter-16.html

Rubin, D. B., 1986. Statistical matching using file concatenation with adjusted weights and multiple imputations. *Journal of Business & Economic Statistics,* 4(1), pp. 87-94.

Rudra, M., 2014. *Application of Imputation Methods in the Analysis of Freight Trip Generation in the Greater Toronto and Hamilton Area,* s.l.: s.n.

Sharp, J. & Murakami, E., 2005. Travel Surveys - Methodological and Technology-Related Considerations. *Journal of Transportation and Statistics,* pp. 97 - 114.

Simon, J. & Simek, C., 2014. *Chapter 20 Parking Surveys.* [Online] Available at: http://www.travelsurveymanual.org/Chapter-20.html

Southworth, F. et al., 2011. *Chapter 17 Commercial Vehicle Surveys.* [Online] Available at: http://www.travelsurveymanual.org/Chapter-17.html

Southworth, F., Zhang, Y. & Sharp, J., 2010. *Chapter 18 - Workplace and Establishment Surveys.* [Online] Available at: http://www.travelsurveymanual.org/Chapter-18.html
[Accessed 30 June 2018].

Stopher, P., Wilmot, C., Stecher, C. & Alsnih, R., 2003. *Standards for household travel,* Lucerne: 10th Triennial Conference of the International Association.

Tourangeau, R., Conrad, F. & Couper, M., 2013. *The science of web surveys.* Oxford, England: Oxford University Press.

Van der Lann, P., 2000. Integrating administrative registers and household surveys. *Netherland Official Statistics,* Volume 15, pp. 7-15.

Verreault, H. & Morency, C., 2015. *What about Proxy Respondent bias Over Time?,* Montreal : CIRRELT: Interuniversity Research Centre on Enterprise Networks, Logistics.

Verreault, H. & Morency, C., 2018. Integration of a phone-based household travel survey and a web-based student travel survey. *Transportation,* 45(1), pp. 89-103.

Victoria Transport Policy Institute, 2017. Evaluating Active (Non-Motorized) Transport. In: *TDM Encyclopedia.* Victoria: Victoria Transport Policy Institute.

Vovsha, P. et al., 2015. *New features of population synthesis.* Washington, DC., s.n.

Wargelin, L. & Kostyniuk, L., 2014. Self and Proxy Respondents in Household Travel. *Research Gate.*

Wells, T., Bailey, J. & Link, M., 2014. Comparison of Smartphone and Online Computer Survey Administration. *Social Science Computer Review,* pp. 238 - 255.