UTTRI

Research Report

SIMULATING AUTONOMOUS VEHICLES

A Discussion Paper and Research Proposal

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SIMULATING AUTONOMOUS VEHICLES

A DISCUSSION PAPER & RESEARCH PROPOSAL

Prepared for the City of Toronto Transportation Services Division

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1. INTRODUCTION

In a very short time period over the past two-three years the concept of autonomous (self-driving) vehicles (AVs) has captured the attention of the public, multiple levels of government, and the transportation profession. Rapid progress in the on-road demonstration of various levels of autonomous operations, combined with very aggressive competition among the world's largest information technology companies (Google, Apple, Uber, etc.) and automotive manufacturers (Mercedes, BMW, General Motors, Toyota, Tesla, etc.) to be the first to market with robust, practical AVs and AV-based transportation services has led to general consensus that AVs "will be here sooner rather than later" and that they will disrupt the current transportation[1] *status quo* in a way that has not been seen since the introduction of internal combustion vehicles over a hundred years ago.

In 2015 the City of Toronto Transportation Services Division commissioned David Ticoll and the University of Toronto Transportation Research Institute (UTTRI) to prepare a "white paper" exploring alternative future scenarios for AV deployment and the possible impacts of such deployment on the City of Toronto. The purpose of the paper was "to equip City of Toronto decision makers with the information they need to identify and evaluate short and medium term policy, planning, and investment options that pertain to the onset of vehicle automation" (Ticoll, 2015, page 1). In conjunction with the Ticoll report, UTTRI conducted an extensive review of both the academic and popular/professional literature dealing with AVs that was documented in both a summary report (Knowles, et al., 2015a) and a detailed annotated bibliography (Knowles, et al., 2015b).

While recognizing the considerable uncertainty inherent in projecting the future impacts of as-yet unproven technology, the Ticoll report is typical of the current AV discussion in that it takes as given that AVs will, in time, provide major benefits relative to the *status quo* in terms of both roadway operations (increased safety, capacity and speeds, reduced parking requirements, etc.) and trip-makers' travel experience. While some of these assumptions may be reasonable, our review of the literature indicates that very little substantive exploration of many of them has occurred to date. In particular, it is far from clear at this moment in time that the claims concerning capacity and speed improvements will necessarily be achieved within the complexity of actual urban networks. Similarly, the travel demand responses to AV-based services are far from understood, as are the potential impacts of such services on transit services, urban form, etc.

The purpose of this paper is, first, to enumerate a number of areas of current significant uncertainty concerning potential AV impacts on roadway operations, travel demand and urban form, and, second, to propose a coordinated research program to systematically investigate these issues. A fundamental assumption in the construction of the proposed research program is that advanced simulation modelling methods can provide a primary analysis tool to move beyond the qualitative assertions typical of current discussions towards a much more rigorous, quantitative exploration of key AV design and performance issues. In particular, simulation models can provide a "virtual laboratory" within which controlled "experiments" can be conducted to test

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[1] As well as potentially many other aspects of urban life, including urban form, the delivery of City services, etc.

alternative assumptions concerning AV operations and impacts within realistic, city-scale representations of the transportation system, the urban form within which this system is operating and the travel market that the system is intended to serve.

In developing this discussion of issues and the associated proposed research program the 2015 literature review is revisited with respect to the current state of art/practice with respect to AV-related simulation modelling. This re-review identifies both (a) what has already been learned from simulation studies and (b) the strengths and weaknesses of the simulation modelling efforts to date. This provides the point of departure for the proposed research program, which proposes both methodological advances (to improve the state of the art in AV-relevant simulation methods) and enhancement of our substantive understanding of potential AV impacts on transportation system performance, travel demand and urban form.

The results of this research should provide:

- Enhanced understanding of the feasibility / likelihood of various AV-based technologies and services for practical, large-scale application in Canadian urban areas.
- Improved insights into likely the impacts, benefits and costs of AV implementations.
- Clearer policy guidance concerning the need / options for government responses to AV implementations (regulations, public sector technology adoption policies, etc.).
- Improved tools (models and associated analytics) for AV-related policy analysis and decision support.

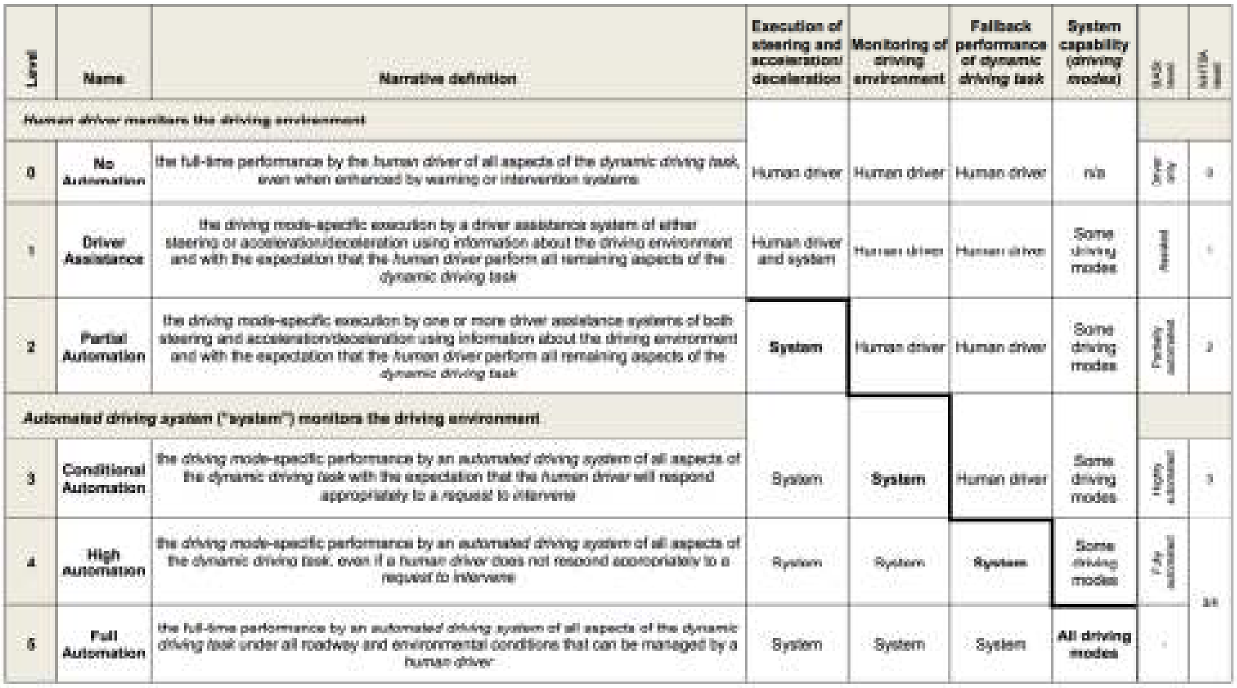
Section 2 of this report briefly defines key terms and concepts used throughout the rest of the report. Section 3 then presents and discusses an extensive (but undoubtedly not totally comprehensive) typology of AV-related policy-related research issues. Building upon the Section 3 discussion, Section 4 describes a simulation-based, virtual laboratory for systematically investigating AV design, policy and operations issues in a rigorous scientific research program. The scope of this laboratory's capabilities and the research questions that can be investigated with it is very scalable, depending on the resources available to support the research, as well as the questions which are of immediate interest. Given this, Section 5 presents a modular approach to possible workplans, budget and schedule for the proposed research program.

Note that this report deals only with person-based travel within large urban regions. That is, it does not address other possible AV applications (freight, off-road, etc.) or rural / intercity travel.

2. DEFINITION OF TERMS

SAE (2014) defines 5 levels of increasing automation in vehicles as listed in Table 1. The issues of interest within this paper (Section 3) all relate to situations in which essentially full (Level 5) automation is available and, typically, is ubiquitously available. Significant issues exist with respect to the transition from the current *status quo* (no fully automated vehicles on urban roads) to this anticipated ubiquitous AV future state. These issues certainly are of interest to UTTRI and could well be included in the research activities sketched below. To keep the discussion somewhat simplified for present purposes, however, these transition research issues are not explicitly dealt with in this paper.

Table 1: Levels of Vehicle Automation *(Source: SAE, 2014)*



Level	Name	Narrative definition	Execution of steering and acceleration/ deceleration	Monitoring of driving environment	Fallback performance of dynamic driving task	System capability (driving modes)	BASt level	NHTSA level
Human driver monitors the driving environment								
0	No Automation	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a	Driver only	0
1	Driver Assistance	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes	Assisted	1
2	Partial Automation	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes	Partially automated	2
Automated driving system ("system") monitors the driving environment								
3	Conditional Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task* with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes	Highly automated	3
4	High Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes	Fully automated	3/4
5	Full Automation	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**	-	

Closely connected with the concept of autonomy is that of connectivity. A "connected" vehicle is one that can directly communicate with other vehicles (V2V) and/or the internet (V2I, and, hence, to real-time control systems and, more generally the Internet of Things (IOT)) through a variety of possible communication channels. It is often assumed that a future end state will exist in which vehicles are both fully autonomous and connected. Limited connectivity currently exists in terms of onboard navigation systems in many cars which are continuously communicating with a "home server" – typically the auto manufacturer or other company providing the navigation service. "Full", universal connectivity, however, is still a significant technical challenge in a variety of ways (communication bandwidth, data storage, computing power, etc.), and so it is likely that significantly autonomous vehicles with at best limited connectivity will be in operation before full connectivity is achieved. The relative performance of autonomous-only, connected-only and autonomous-and-connected vehicles is of considerable interest. The discussion in the remainder of this paper simply uses the term autonomous vehicle (AV), but it should be noted, that in general the issue of connectivity (or lack thereof) will be a key issue in most of the research that will be undertaken. In particular, it is arguable that the full roadway performance benefits of AVs may only be achievable with high levels of connectivity – a question that requires substantially more investigation.

It is also commonly assumed that AVs will eventually be electrically-powered (or at least non-fossil-fuel-based). It is argued that AVs are expected to be much lighter than current autos, thereby improving the performance of even current electric vehicle (EV) technology and, hence, accelerating the widespread adoption of EVs. This convergence of AV and EV technology is certainly plausible, evidence of which is currently available in many of the prototype vehicles currently being tested. One way or another, "de-carbonization" of the road fleet is essential if aggressive greenhouse gas (GHG) reduction targets are ever to be met. This issue is returned to in Section 3.5.

A final key concept requiring introduction is that of alternative service concepts that might accompany the introduction of AVs. These include:

- Privately owned and operated AVs. This is the current *status quo* situation in which individual households continue to own/lease cars exclusively for their own personal use, with the only change being that the cars are now autonomous.
- Privately owned AVs with shared usage. It is possible that people will be able to rent the usage of their privately owned AVs to others when they are not using them – similar to current car-sharing services that have emerged recently in many cities.
- Taxi-like operations in which fleets of AVs are owned and operated by private companies and provide taxi-like services to individuals on an on-demand basis, replacing current conventional taxi and Uber/Lyft human driver-based systems.
- Public transit applications in which AVs provide linkages between trip origins and destination to/from transit stations, possibly eliminating/reducing the need for local bus services. In particular, such services may be a very attractive solution to the so-called "last mile" problem in low-density suburban areas in which attractive local transit connections to higher-order rail transit is very difficult to provide cost-effectively.

The future is likely to involve some combination of all of these service concepts, but the extent and nature of service implementations will significantly impact travel demand (particularly transit usage), the demand of automobiles, vehicle design (e.g., number of passengers) and roadway performance, among other issues.

3. AV DESIGN & POLICY ISSUES

3.1 Introduction

This section of the report raises a wide variety of issues, opportunities, concerns associated with ubiquitous AV operations that are currently the source of significant uncertainty and so are deserving of further research in support of improving our understanding of both the likely impacts of such operations and the likely policy considerations needed to ensure that the implementation of AV services results as best as possible both in maximizing net social benefits and avoiding significant adverse unintended consequences. Although interrelated, for ease of discussion these issues are divided into the following topic areas, which are discussed in turn in the following sub-sections:

- Highway performance.
- Urban street performance.
- Travel demand impacts.
- Energy consumption and environmental impacts.

3.2 Highway Performance

The basic physics of highway operations is based on the fundamental equation of traffic flow theory:

$$q = kv \qquad [1]$$

where:

q = Average flow on a finite section of highway over a finite time period (veh/hour)
k = Average density within the section during the time period (veh/km)
v = Average speed of vehicles with the section during the time period (km/hour)

Equation [1] does not necessarily hold instantaneously at any point in space, but it must hold over a finite period of time for a given section of highway.

Average speed, in turn, is a function of average density:

$$v = f(k) \qquad [2]$$

This average speed-density fundamentally defines the nature of the highway's performance over time.

At the micro level of individual vehicle movements along a highway, this movement can be completely characterized by the combination of its car-following behaviour (i.e., how the vehicle accelerates and decelerates so as to maintain a desired speed and spacing relative to the car in front of it in the lane) and its lane-changing / gap acceptance behaviour (i.e., how and when the vehicle changes lanes, either to pass slower-moving vehicles or to position itself to exit the highway). Many models of both car-following and lane-changing exist. For example, a very typical car-following model is given by:

$$\ddot{x}_{n+1}(t+\Delta t) = \lambda_0\, \dot{x}_{n+1}(t)^M\, [\dot{x}_n(t) - \dot{x}_{n+1}(t)] / [x_n(t) - x_{n+1}(t)]^L \qquad [3]$$

where:

n = Index indicating the nth car in a vehicle stream
$n+1$ = Index indicating the car immediately upstream vehicle n
$x_n(t)$ = Location of vehicle n at time t (x measured from an upstream origin point)
$\dot{x}_n(t)$ = Velocity of vehicle n at time t
$\ddot{x}_{n+1}(t+\Delta t)$ = Rate of acceleration of vehicle n+1 in the next time interval Δt
L, M, λ_0 = Parameters

It is interesting to note that equation [3] can be integrated under assumptions of homogeneous flow conditions to generate the macro average speed-density relationship (equation [2]) that corresponds to the micro behavioural model. For example, if in equation [3] $M = 0$ and $L = 2$ then the classic Greenshield's speed-density relationship results:[2]

$$v = v_f(1 - k/k_j) \qquad [4]$$

where v_f is the roadway free-flow speed and k_j is the roadway jam density. This relationship between micro and macro behaviour is very illuminating in that it both validates the basic behavioural principle of car-following (since it generates observed macro behaviour) and provides a strong basis for developing both micro and macro models of traffic flows (i.e., a macro model should correspond to a "sensible" micro model and *vice versa*).

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[2] Greenshiled's model is not an overly realistic model of traffic flow, but it is often used, as herein, for illustrative purposes, given its simple formulation.

The capacity of a highway is the emergent outcome of its geometry and operating characteristics. That is, for a given geometry (number of lanes, lane width, curvature, grade, etc.), a highway's capacity is determined by its speed-density relationship (or, equivalently, its underlying micro car-following behaviour). In the case of a highway following Greenshield's formula, for example, this capacity (maximum through-put) will occur at a density of $k_j/2$. Thus, in order to increase a highway's capacity (for a fixed geometry) one must somehow alter the highway's speed-density behaviour in a way that increases the maximum achievable flow.

Equations [1] and [2] are static views of roadway performance, whereas equation [3] is a dynamic representation, describing the evolution of vehicle flow over time and space. Note that it inherently requires a simulation framework for implementation: the only way to describe the roadway's system state over time and space (in terms of the locations and speeds of the vehicles using the roadway) is to execute equation [3] vehicle-by-vehicle over a sequence of time steps.

Another important property of a roadway's performance is the extent to which it is stable over time. Stability means that minor local perturbations in speed and flow tend to diminish rather than grow over time. Clearly, this is the "normal" case for highway flows under "normal" operations. Also clearly, highway flows can become unstable under certain conditions, most typically as flows approach capacity or under severe transient conditions (e.g., an abrupt stoppage or slowing down of flow). It can be shown that for a highway to display stable operations the parameters of its car-following behaviour must fall within a certain range.

Accidents occur when the car-following and/or lane-changing behaviour of one or more vehicles "fails" and two or more vehicles collide. This can happen, of course, for many reasons, notably driver error, vehicle malfunctions, poor weather conditions, etc. Note that neither equation [2] nor [3] account for such failures, and note that no standard traffic simulation model permits accidents to occur within its simulations. In order to incorporate accidents within a model one would have to simulate the events which can give rise to an accident as well as the transient responses of vehicles to such events.

So, what does any of this theory have to do with AVs? It is generally asserted that AVs will:

1. Increase highway capacity.
2. Increase highway speeds.
3. (Implicitly) generate stable flows across normal operating ranges.[3]
4. Significantly reduce accidents.

If (1) and (2) are to be achieved, then AVs must change the underlying car-following relationship for highways (or, equivalently, the macro speed-density relationship) by allowing vehicles to consistently travel faster and closer together. This must be accomplished in a way that maintains flow stability (criterion 3) and improves safety (criterion 4). Safety (accident reduction) must be accomplished by reducing accident-generating events, reducing "driver" reaction times and/or improving driver" responses to such events (presumably all three).

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[3] I.e., the question of flow stability is not generally discussed by AV advocates, but clearly this is the implicit assumption being made.

While fifth-generation AVs may well meet all these criteria, at the moment this is simply assumed rather than robustly demonstrated, especially for complex real-world highway situations involving high flow levels, mixed fleets (both in terms of vehicle types and the percentage of AVs in the flow), and adverse weather conditions, among other possible factors. The role of connectivity in achieving these benefits also required more investigation.

Further, virtually all discussion of AV performance appears to assume unrestricted highway operations. In particular, it ignores the effect of access and egress ramp flows on mainline highway operations. Access flows entering a freeway may be accommodated under most conditions without undue disturbance of mainline flows, assuming a high degree of coordination among vehicles (either explicitly in the case of connected vehicles or implicitly in the case of unconnected AV protocols for cooperative operations), although even in this case some effects of flow mixing on roadway capacity can be expected as vehicles adjust to accommodate the merging flow.

Egress ramp flows, however, potentially may have significant impact on mainline operations if queue spillbacks from the egress ramp onto the mainline occur. Such spillbacks might well occur if delays occur at the junction of the ramp and the local arterial road system. As discussed below, even under ubiquitous AV operations it is possible that urban street capacities may not increase significantly. If this is the case, then local streets may not be able handle high egress flow volumes from a freeway. In such cases, egress ramps may constitute a significant bottleneck for freeway operations, possibly nullifying much of the potential capacity gains of free-flow AV operations.

3.3 Urban Street Performance

3.3.1 Introduction

Urban streets behave much differently than freeways. Their performance (average speed, capacity, etc.) is largely dominated by intersections, particularly signalized intersections. They are also extremely more complicated operating environments given the wide mix of vehicles (cars, bicycles, transit vehicles, delivery vans, trucks, etc.), uses (thoroughfare, pedestrian crossings, parking and delivery, etc.) and the largely uncontrolled nature of roadway entry and exit.

Relatively little attention seems to have been paid to date to understanding AV operations and performance in dense urban street environments, particularly with respect to the impact of AVs on street network capacity. As with freeways, there is a general assumption that street capacity will increase. This view is largely based on some combination of three assumptions:

- Fully automated operations will permit significant increases in signalized intersection capacities.
- AVs will eliminate the need for on-street parking thereby freeing-up parking lanes for vehicle movements.
- AV-based car-sharing will reduce the number of vehicles on the road and/or the number of vehicle-kilometres-travelled (VKT), thereby freeing up capacity for the remaining vehicles.

Each of these assumptions, however, are open to question and should be analyzed in greater detail.

3.3.2 Signalized Interaction Operations

The assumption that ubiquitous AV operations will radically change intersection operations (in the extreme, eliminate the need for signalization) seems to be simply wrong-headed. Signalized intersections will remain essential in most urban contexts to safely coordinate pedestrian and bicycle movements, even if they (theoretically at least) are not required to control AV operations. If this is the case, then it is unlikely that street network capacity will increase significantly. This being said, room undoubtedly exists for improved traffic signal control strategies that will exploit AV (especially connected AV) technology. One example of this is the work of Dresner and Stone (2005, 2007), Fajardo, et al. (2012) and Au, et al. (2015), who have developed AIM (Autonomous Inersection Management), an "automated intersection control protocol" for handling semi-AV flows through intersections. Noting that existing powerful road network microsimulators such as VISSIM,[4] CORSIM[5] and SIMTraffic[6] are somewhat limited in their ability to deal with the dynamic, new control protocol that they were proposing, they developed their own intersection microsimulator. This is not an uncommon approach to the problem of simulating AV and associated control systems

Greater improvements in street network performance may well result from ubiquitous V2V and V2I connectivity rather than autonomous operations per se, in terms of facilitating dynamic, real-time, adaptive traffic signal control. The MARLIN system developed at the University of Toronto is one example of such a system that is already in field tests and that would benefit greatly from enhanced vehicle connectivity (El-Tentawy, et al., 2013)).

Similarly, the complexity of street operations will continue to necessitate moderate speeds to ensure safe operations, even under autonomous control, again implying at best modest improvements in average speeds.

3.3.3 On-Street Parking

It is argued that AVs will be able to simply drop people off at their destinations, drive away, and then be recalled as needed to pick up people and take them to their next destination. If this is the case, the need for on-street parking would be greatly reduced, or, in many cases, perhaps eliminated entirely.[7] Certainly if this scenario comes to pass valuable lane space will be freed-up for other uses, including improved through-movement of vehicles, representing a clear net social benefit. Note, however, that the dropping-off and picking-up of AV passengers will have some negative impact on roadway operations, since this will require the temporary blockage up curb lanes. While this will be less than the effect of parked cars, some capacity loss will nevertheless ensue.

What the AVs do after dropping off passengers depends on the service model in place. If these vehicles are still privately owned and not engaged in car-sharing operations, then they will still

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[4] http://vision-traffic.ptvgroup.com/en-us/products/ptv-vissim/

[5] http://mctrans.ce.ufl.edu/featured/TSIS/

[6] http://www.trafficware.com/synchro-studio.html

[7] The issue of on-street parking of delivery vehicles presumably remains but is not addressed herein.

need to be parked somewhere (presumably in off-street lots/garages) until recalled by their owners. In this case the need for significant (and expensive) off-street parking facilities will remain. If, on the other hand, the AVs are operated in some form of shared-used operation (either involving privately owned cars being made available for use by others or by taxi-like companies offering the vehicles for use), then the need for off-street parking would be greatly reduced. This would free up valuable land for higher-quality and higher-value uses, again, representing a clear net social benefit.

Finally, with respect to on-street parking it is important to note that this is primarily a policy issue rather than a technical one. We could eliminate most/all on-street parking where it would be advantageous to do so today if we had the political will to implement the policy.

3.3.4 Network Flows & VKT

The possible impacts of AVs on travel mode shares and overall levels of trip-making is discussed in Section 3.4 below. Most scenarios, however, do not imply significant reductions of auto-based travel, and some may imply significant increases in auto-based trips and/or VKT. Further, it is possible that ubiquitous AV operations will generate a significant amount of empty-vehicle, “dead-heading” travel as AVs either travel to/from parking locations and/or as they travel from their last drop-off to their next pick-up point. Thus, it is very possible that AVs will result in increased loads on the road network, rather than a net decrease, with the net impact on roadway performance depending on whether they simultaneously generate increased roadway capacity to accommodate the increased load on the network.

3.4 Travel Demand Impacts

3.4.1 Introduction

Person-based travel within an urban area is the derived demand (emergent outcome) of the need for people to engage in out-of-home activities (work, school, shopping, etc.) at locations that are dispersed in space and time within the region. Travel decisions include how many trips to make each day for what purposes, at what time day, by what travel mode and path (route) through the multi-modal urban transportation network. These decisions depend upon a wide variety of factors, including the personal attributes of the trip-makers, the household context (resources, constraints, interactions) within which trip-makers reside, the urban form (both “macro” population and employment distributions and “micro” neighbourhood design features), and the capacities and levels of service of the multi-modal transportation network through which people must navigate during their daily travel.

Ubiquitous AV services will certainly change current travel patterns and modal usage in a wide variety of ways. Possible impacts of potential significant impact (discussed in the following sub-sections) include:

- Redefinition of auto-based personal travel.
- Public transit impacts.
- Urban form impacts.

The extent to which such shifts in behaviour will actually occur depends on the spatial, temporal and socio-economic details of the urban travel market, as well as the actual levels of road system performance improvements obtained in an AV-based future. These can only be investigated through formal, extensive simulation modelling of urban transportation supply and demand processes.

3.4.2 Auto Demand Impacts

If AVs and new AV-based services make travel faster, more convenient and/or cheaper (and, thereby, improve people's accessibility to activities and services) they may change trip rates (people are able / willing to travel more), destinations, time of travel and/or travel mode. In particular, if the auto becomes even more attractive than it currently is for travel then it might divert significant numbers of trip-makers from public transit to auto-based modes. Anecdotally, we are perhaps seeing some evidence of this trend in the widespread use of Uber/Lyft services arguably attracting trips away from transit in some cities. While such a modal shift presumably is of benefit to the individual trip-makers (otherwise they presumably would not have switched modes) it is not clear whether this represents a net social benefit or not, and this question is worthy of much more detailed investigation.

Further, returning to the issue of parking, the cost and convenience of parking generally is a major determinate of auto mode choice. If parking, one way or another, becomes a much less onerous component of auto trips this may also induce large mode shifts to auto, with, again, potentially unwelcome impacts.

3.4.3 Public Transit Impacts

AV services potentially might also have beneficial impacts on public transit usage if, as briefly noted above, they can provide significantly improved access/egress to/from higher-order transit services in low-density suburban neighborhoods that currently are difficult, if not impossible, to serve cost-effectively with conventional bus services. If successfully implemented, such "last mile" solutions might have significant social benefits in terms of improved trip-maker experiences, increased transit usage and significant reductions in the need for inefficient, costly, polluting suburban bus services.

As with all aspects of AV-based travel, different service models are conceivable here, ranging from the laissez-faire (letting the private sector provide the service if it is profitable) to direct public planning and/or operation of formal transit access/egress services.

3.4.4 Urban Form Impacts

It is sometimes argued that ubiquitous AV services will encourage urban areas to "sprawl" even more than they currently have, since people might be willing to live much farther from work (or other urban amenities and services) given the ease of long-distance travel that AVs will provide. Certainly throughout history we have seen urban areas decentralize as transportation technology improvements permit higher-speed travel over longer distances.[8]

Again, this may represent improvements in individuals' benefits, but, given the many "externalities" associated with low-density sprawl, it is not clear that this is a socially desirable future state. Also, as with virtually all issues raised above, current qualitative discussions

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[8] Steam and then electric railways began this process in the 19th Century, while the automobile vastly accelerated this process in the 20th Century.

possibly ignore the "equilibrating" effects that would be at play in practice, in which this "centrifugal" tendency for people to move further out will generate more traffic on roadways, which, depending on the net effects of AVs on performance discussed above, may nullify some/most of the service improvements, thereby reducing the net attractiveness of decentralization.

These are not easy hypotheses to test, since this really requires a fully integrated land-use – transportation model system, in which residential and employment locations evolve endogenously over time in response to transportation system changes in accessibility, among other factors. UTTRI has been developing for some time such a model system for the Greater Toronto-Hamilton Area (GTHA) – the ILUTE (Integrated Land-Use, Transportation, Environment) agent-based microsimulation system for modelling the evolution of urban demographics, economic activity, land use, travel behaviour and environmental impacts, which can be adapted and extended to investigate these issues.

3.5 Energy Usage & Environmental Impacts

As noted above, it is often assumed that AVs will be electrically powered. From a GHG and climate change perspective this is highly desirable.[9] As with all discussion of EVs, significant issues currently exist with respect to:

- Developing the re-charging network required to service an electric fleet.
- The timing and size of the load that will be placed on the power generation and distribution systems by widespread EV usage is also a concern.
- The potential to integrate EVs with local (possibly household-based) distributed electricity generation systems (wind, solar, etc.) as well as the role of the EV as a power generator as well as a user of electricity.

If AVs are not electrically powered (perhaps at least in the short/medium term) then the usual issues with auto-based transportation of GHG and air pollution emissions will remain and need to be assessed.

4. A SIMULATION-BASED VIRTUAL LABORATORY FOR AV EXPERIMENTATION

4.1 Introduction

The wide range of issues briefly discussed in Section 3 cover a broad spectrum of spatial and temporal scales as well as imply the need for detailed representations of urban form, network and socio-economic attributes of the trip-making public. Given the absence of operational AV systems, the only viable method for rigorously investigating these issues is by constructing a computer simulation environment – a "virtual laboratory" – within which alternative design concepts, assumptions about AV operating characteristics, assumptions about traveller behavioural responses, etc. can be systematically and comprehensively tested within a controlled experimental research environment.

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[9] It is, of course, highly desirable for the case of non-AV vehicles as well.

Numerous examples of simulation models of various aspects of AV operations and/or demand have been developed over the past 10-20 years. A good review of AV simulators which provide detailed simulation of the movement of an AV on a street is provided by Figueiredo, et al. (2009). This paper also presents the authors' proposal for development of an improved simulator relative to the reviewed state of the art. While useful for some purposes, in general, the level of detail discussed in this paper deals with a much higher level of operational fidelity than is necessary for most of the simulation-based analyses discussed in this paper. These generally can make do with less-detailed representation of the "inner workings" of the AV communications and control system, instead adopting a more holistic, higher-level representation of AV behaviour. Similarly, Isa and Jantan (2005) and Falcone, et al. (2007) both presents detailed models of AV control systems which may provide useful equations of motion for an AV, if such detail is required in a traffic simulator.

Perhaps the most notable example of a recent, fairly comprehensive simulation modelling effort similar to what is proposed below in this report is the International Transport Form (ITF) agent-based simulation work in Lisbon, in which both the demand for AV services and the routing of AVs through the road network are simulated in some detail (OECD, 2015). This model represents on possible point of departure for the agent-based microsimulation modelling work proposed below.

The ITF report also reviews modelling efforts by Fagnant and Kockelman (2014) for Austin, TX, Spieser, et al. (2014) for Singapore; taxi fleets in New Jersey (Zachariah, et al., 2013); and New York City (Santi, 2014); and the Burns, et al. (2013) simulation of centrally-dispatched AV fleet operations in three different urban settings: Ann Arbor MI, Babcock Range FL and Manhattan NY. Ford (2012) similarly reviews modelling efforts by Ludman, et al. (1996) and Keting, et al. (2009). Spieser, et al (2014) also reference simulation efforts by Barth and Todd (1999), Kek, et al, (2006), Papanikolaou (2011), Efthymiou (2012), and Barrios and Godier (2014).

Such a virtual laboratory as is being proposed in this report will require the coordinated use of a variety of simulation models operating at different levels of spatial and temporal precision (aggregation), applied to different specific research questions. That is, it is not possible to construct a "universal" model that could be used to investigate all possible AV-related questions. Rather, what is required is the thoughtful development and use of a suite of modelling and analysis tools in as integrated and consistent a manner as possible, working within a common, comprehensive database and set of scenarios/assumptions. Note that not only is this the only feasible approach to a problem of such depth and breadth, it also very practical in that it permits an incremental, modular approach to building a broad research program one model and one (or a small handful) of model applications / research questions at a time.

UTTRI is in the process of building exactly this sort of virtual laboratory. Branded *iCity*, this emerging research program is briefly described in Section 4.2. iCity provides the institutional and computational environment within which a powerful, comprehensive simulation environment can be constructed to explore the wide range of AV-related issues raised in Section 3. This simulation-based AV laboratory is described in Section 4.3.

4.2 iCity: An Urban Informatics Laboratory

iCity builds on UTTRI's deep expertise in simulation to develop and apply advanced data, analysis and visualization capabilities to find innovative ways to improve urban transportation system performance and design efficient, sustainable cities for the well-being of individuals and society. It applies urban informatics – the combination of high-performance computing (HPC), massive "big data" sets, and advanced analysis, simulation and visualization software -- to the analysis of major urban transportation problems. iCity is a computational "virtual lab" for analysis and design in which powerful, comprehensive computer models simulate the evolution of urban spatial socio-economic systems (transportation, the regional economy, etc.) in response to a wide variety of scenarios and policies. Combined with equally powerful and advanced visualization capabilities, this virtual lab provides the analytical environment needed to develop and test:

- Hypotheses about urban system processes system interactions to develop deep understandings of cities as systems of systems.
- Practical solutions to specific problems that begin with the "here" of the current metropolis and recognize that getting to a more resilient and sustainable "there" requires finding feasible pathways into the future.
- A rich suite of performance measures, detailed benefit/cost distributions, etc. for comprehensively understanding the impacts of alternative policies.
- New tools, methods and software for real-time transportation system management and control.
- Compelling, readily transmittable "stories" demonstrating the feasibility and efficacy of the solutions developed: why they are better than the status quo and how they can feasibly come to be.

iCity builds upon the University of Toronto's world-leading urban simulation modelling capabilities. It consists of a trans-disciplinary research team seeking new integrated approaches to understanding and re-vitalizing city systems. It adopts a "systems of systems" approach in which it is recognized that the design of any one component of the city, such as transportation, affects not only this system but all the others with which it interacts: housing, the regional economy, etc. These systems, in turn have "feedback" effects on transportation (shifts in population affect travel demand and transport system performance). A holistic, comprehensive approach to urban system design is therefore essential if major unintended consequences are to be avoided and if implemented policies and technologies are to cost-effectively achieve their intended outcomes with maximum benefit. Without an integrated analysis of both the transportation and regional economic systems it will be difficult, and perhaps impossible, to find the truly desirable solutions that we need. Further, in the absence of such integrated analyses, it is often easy for interest groups to argue for parochial, vested or ideological alternatives that are not objectively defensible but that are difficult to dismiss due to lack of compelling, objective evidence concerning their benefits and costs relative to other alternatives.

iCity is also a partnership enterprise, involving strong collaborations with leading private sector firms in both the Information Technology (IT) and transportation sectors, as well as municipal, regional and provincial public sector agencies. iCity has three over-arching objectives:

1. Exploit advanced Information and Communication Technologies (ICT) and iCity partner expertise to develop tools, models and software for:

   a. Advanced methods for transportation demand and performance data collection.
   b. Real-time operational control and short-medium term tactical planning of transportation systems to maximize the cost-effective use of existing infrastructure and services.
   c. Improved strategic planning, design, policy analysis and evidence-based decision-support of transportation systems.
2. Build upon the Objective 1 advances to support:
   a. Continuing development of Ontario's urban informatics industry by developing new marketable products, services and expertise.
   b. Strengthening Ontario's engineering and planning professional consulting community by providing new planning and design tools, capabilities and concepts.
   c. Improving public sector policy analysis and decision-making at municipal, regional, provincial and federal levels, both by providing new decision-support systems and by undertaking numerous case studies of critical policy issues currently facing Ontario's urban regions.
3. To mentor and train the next generation of urban informatics and urban transportation engineering and planning professionals (HQP) through graduate student, post-doctoral fellow and technical staff participation in all facets of the research, as well as through our Youth Outreach activities.

The iCity approach recognizes that trying to "understand" a city across all its scales and processes, however, is a challenging task. A viable approach for dealing with such complexity is a hierarchical, nested one, in which the city is modelled at multiple scales and levels of detail. At the highest level is an integrated representation of the region as a whole that focuses on the interactions and feedbacks among multiple systems. The intermediate level involves models of individual systems, which treat the effects of other systems as exogenous inputs. The lowest level deals with individual system elements processes in detail. Not only does this provide a pragmatic way of preserving an overall holistic perspective while not being overwhelmed by the detailed complexity of the city, it also provides a coherent framework for systematically focussing on individual system components and issues. As a practical matter, much of a system's design occurs at the component level, and there is great utility in being able to focus in detail on a component while being able to appropriately account for its interface with the rest of the system.

Operationally, the iCity program currently consists of two major projects;

- *iCity-ORF: Urban Informatics for Sustainable Metropolitan Growth*: This is a $2.95 million, four-year project funded by the Ontario Research Fund – Research Excellence program, with matching contributions from IBM Canada, Cellint Traffic Solutions, City of Toronto and Waterfront Toronto.
- iCity-South: The Latin American Development Bank (CAF) is sponsoring an urban informatics for sustainable urban mobility program for Latin American cities. To begin, two small research projects have recently been launched: an agent-based microsimulation modelling exercise in Asuncion, Paraguay, and an advanced travel behaviour data collection study in Montevideo, Uruguay.

4.3 iCity AV Simulation Laboratory (iCity-AVL)

UTTRI has a long-standing, international reputation in transportation simulation modelling, particularly microsimulation modelling with respect to both road and transit network route choice and network performance and regional travel demand modelling. We work with a variety of commercial (Paramics, Aimsun, Vissim, Emme, MassMotion, etc.), open-source (Dynus-T, MATSim, etc.) and UofT-authored (XTMF, GTAModel, MILATRAS, etc.) simulation software packages to address a wide range of short-run operational and long-run planning research questions. It is proposed that we build upon and consolidate these capabilities within the *iCity AV Simulation Laboratory* (*iCity-AVL*). iCity-AVL will undertake a wide range of AV-related research tasks utilizing (and when necessary, developing) cutting edge simulation methods and associated advanced analysis and visualization methods.

As sketched in Section 3, possible research topics are very wide ranging. To address these topics iCity-AVL will include in its "toolbox":

- Road and transit network microsimulation models. These will range from major commercial software packages to custom-built, problem-specific "toy" models designed to investigate very specific, individual behaviours.
- Multi-modal simulations to deal with AV-transit interactions.
- Regional-level activity-travel, agent-based microsimulation models (e.g., GTAModel V4.0, developed for use by City of Toronto Planning) to investigate regional network level issues.
- The ILUTE integrated urban modelling system can be used to investigate potential urban form and environmental impacts of AVs.

While hypothetical, abstract, "toy" models are mentioned above as useful tools for certain types of detailed, exploratory experiments, emphasis will be placed on investigating AV performance and impacts within real-world, large-scale networks, taking into consideration practical, network-level interactions, and the demand-supply and other systems-of-systems feedbacks that occur in real cities and that must be understood if the actual (as opposed to hypothesized) likely impacts of AVs are to be estimated. The Greater Toronto-Hamilton Area (GTHA) – or appropriate sub-sections thereof – will be the primary initial "testbed" for iCity-AVL investigations, although extension of the research to other urban regions is certainly feasible as need and opportunity arise.

Data to support simulation model develop and application will come from a variety of sources. Much relevant data are already in hand, including Transportation Tomorrow Survey (TTS) travel behaviour data (maintained by UTTRI's Data Management Group (DMG) on behalf of GTHA transportation agencies), extensive traffic data from MTO's COMPASS and the City of Toronto's RESCU systems (via UTTRI's ITS Centre). Relevant data are also being collected as part of the iCity-ORF project, including smartphone app-based trip traces, Cellint cellular data, and other "big" passive traffic datasets.

5. iCITY-AVL RESEARCH PROGRAM DESIGN

The intent of iCity-AVL is to be an on-going research program undertaking systematic investigations of a wide range of AV-related network and service designs, planning and policy issues and decision support. To successfully address this mandate will require secure multi-year funding to support a critical mass of research staff and students and the development and maintenance of a state-of-the-art simulation and visualization computer laboratory. This laboratory will be housed with UTTRI's ITS Centre and Testbed, which will provide the hardware and operating environment for iCity-AVL.

One model for iCity-AVL operations is provided by UTTRI's Data Management Group (DMG) and Travel Modelling Group (TMG), both of which are on-going programs funded by a consortium of GTHA transportation planning agencies. Each year a work program for the year consisting of specific tasks and deliverables is approved by a steering committee and progress on the previous year's work program is reported. In this way, long-term objectives are addressed while short-term results are delivered in a systematic, coordinated research program. In the case of iCity-AVL both the Province of Ontario and the Federal Government appear to be promising sources of funding, given their expressed interests in AVs.

A research program such as this is readily scalable: more resources more or less linearly translate into greater productivity. A certain minimum level of investment, however, is required if the program is to be viable. Table 2 provides, for discussion purposes only, a possible draft budget in the order of $250,000 per year that would support a very strong AV simulation research program.

Table 2: Example iCity-AVL Annual Budget

Budget Item	**Number**	**Unit Cost**	**Amount**	**Notes**
Network Modeller & Programmer	1	80000	80000	Includes fringe
Graduate Students	4	20000	80000	
Summer Undergraduate Research Assistants	1	6000	6000	
Hardware updates			4000	
Software maintenance			3000	
Annual Symposium			5000	Showcase & disseminate research results
Miscellaneous Operating Expenses			500	
Sub-total			178500	
University Overhead @40%			71400	
ANNUAL TOTAL BUDGET			249900	

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