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Measuring the completeness of complete streets

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ABSTRACT

A tool for measuring the "completeness" of a complete street has applications in developing policy, prioritising areas for infrastructure investment for a network, and solving the right-of-way allocation problem for individual streets. A literature review was conducted on the state-of-art in the assessment complete street designs. Complete streets assessment requires a context-sensitive approach, thus context-sensitive standards of "completeness" must first be established by combining a street classification system with sets of priorities and target performance levels for the different types of streets. Performance standards should address a street's fulfilment of the movement, environmental, and place functions, and be flexible enough to account for the many ways that these functions of a street can be fulfilled. Most frameworks reviewed are unsuitable for evaluating complete streets because, with few exceptions, they guide street design by specifying the design elements for inclusion on the street. Secondly, the performance of a street can be assessed according to transportation, environmental, and place criteria, and compared to the target performance levels specified by the street's classification. As there are many different impacts to consider on a street, additional work is required to define the priorities and performance objectives for different types of streets.

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Introduction

"Complete streets" are an emerging concept in North American transportation planning and design discourse. The complete streets movement emerged to expand the focus of transportation design from streets from automobility to the accommodation of all modes of travel (McCann, 2013). Thus, complete streets are broadly defined as streets that can safely accommodate all road users, regardless of mode of travel or ability (National Complete Streets Coalition, 2011), though complete streets designs and policies sometimes also have social and environmental goals and benefits (Litman, 2015; National Complete Streets Coalition, 2016).

Most complete streets policy and literature addresses the qualitative goals of complete streets, the before-and-after effects of complete streets projects, and the array of different

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complete street design elements. Less attention has been directed towards the quantitative assessment of the adequacy of existing and proposed street designs. There is no comprehensive framework available for quantitatively assessing "completeness" – referring to the extent to which a complete street fulfils its required functions.

However, a strong, quantitative evaluation framework to complement the predominantly qualitative approach to complete streets would be helpful in fully understanding the trade-offs inherent in complete street design. Kingsbury, Lowry, and Dixon (2011) criticise the prevailing qualitative "know it when you see it" attitude towards complete street evaluation as "unconstructive" in determining where to make infrastructure investments. This qualitative approach also makes it difficult to reconcile the many competing demands on a street when designing a street, a problem that is complicated when improving fulfilment of one function of a street may negatively impact another, or when the available space is not sufficient to accommodate all the desired street elements.

Furthermore, complete streets have large sets of potential competing priorities, where the importance of each priority will vary depending on the context of the street and its role in the network: not every street is intended or suitable for the accommodation of every user mode or street function (Sousa & Rosales, 2010). Formal quantitative identification of the different priorities of different types of streets is necessary to begin to comprehensively understand the trade-offs between a street's required functions. What Kingsbury et al. (2011) call the "know it when you see it" identification of a complete street is insufficient: the needs of complete streets need to be linked to a context-sensitive quantitative assessment framework to effectively develop complete streets design and policy.

Thus, a literature review was conducted to investigate how the completeness of streets can be defined and evaluated. The paper approaches this problem in three parts. First, frameworks that can define the priorities and performance standards for different types of streets are reviewed. Second, the impacts of complete streets and ways in which they can be assessed are identified. Finally, two potential applications for a quantitative definition of completeness are discussed. The review focuses on research and policies from North America published in the last 10 years. The material reviewed consists mainly of articles, manuals, and city guidelines, and is not limited to methods designed specifically for complete streets.

Defining completeness

What difference is there between the traditional concept of a street, and a complete street? Conventionally, a street is a link between places, but it can also be a place of recreation, socialisation, and environmental benefit. Complete streets are primarily defined as streets that can safely accommodate all road users, regardless of mode of travel or ability (National Complete Streets Coalition, 2011). However, complete streets policies often tout language regarding placemaking directives and environmental best practices (National Complete Streets Coalition, 2016), and complete streets projects are often assessed according to environmental and livability-based criteria (Anderson et al., 2015; Ferguson, Higgins, Lavery, & Abotalebi, 2015; Litman, 2015). Arguably, the objectives of a complete street extend beyond the provision of safe transportation facilities for all users. Thus in this paper, the goals of complete streets design are broadened from safe accommodation of all users, to the recognition that the functionality of a street is dependent on the fulfilment of at least three competing demands: movement, environment, and place (Ferguson et al., 2015; Rodriguez-Valencia, 2014b).

In this paradigm, the movement function is the mechanism of the street that facilitates travel. The environment function involves the aspects of street design that address the street's environmental impacts, including vehicle emissions reduction, stormwater management, and air pollution processing. The place function is that which considers the street as a destination (Rodriguez-Valencia, 2014b). In this paper, "completeness" refers to how well a complete street fulfils these three functions.

Different kinds of street have different functions and priorities. Even the basic functional classification system (i.e. local road, collector road, arterial, expressway) describes the functions of different types of street: in this case, the trade-off between travel mobility and property access (American Association of State Highway and Transportation Officials, 2001). In the complete streets context, the functions of the street and how they can be prioritised are more numerous. Although complete streets are intended to enable safe access for all users on a road, the way and extent to which these users must be served would vary depending on the context of the street (National Complete Streets Coalition, 2011). In certain contexts a complete street may not even require accommodation of every mode (Sousa & Rosales, 2010).

Thus the assessment process for complete streets should be context-sensitive. Different types of streets have different sets of priorities and performance objectives. The relationship between the context and design objectives of a street can be formalised for the evaluation of complete streets by linking target performance levels to a street classification system. However, outside of large cities, complete streets design goals and guidelines that do link to a street classification scheme are very rare (Gregg & Hess, 2016).

Table 1 summarises some frameworks which do use a street classification system to explicitly guide street design by providing context-sensitive design recommendations or assessment criteria. These frameworks were selected to contrast conventional street classification frameworks with context-sensitive street classification and design frameworks. There are examples of how conventional street classification systems guide street design. Nine were selected because they explicitly link a street classification systems with complete streets design recommendations and assessment criteria. Two additional frameworks not explicitly designed for complete streets were also selected as supplementary examples of the use of context-sensitive frameworks in street design.

Classifying complete streets

A complete street classification system describes the relative importance of the different functions of different types of streets. In this paper, the functions of the street are grouped into the movement function, the environment function, and the place function. The relative importance of the different functions on a street vary based on transportation, environmental, and place contexts, thus a street classification system should also take these contexts into account. Transportation context describes the type of users and speed of vehicles on the road, and is usually guided by the road hierarchy. Environmental context describes the relative importance of maximising positive environmental impacts and minimising negative environmental impacts in the design of a street. Place context describes the significance of a street to its users as a social or recreational destination.

Table 1. Street classification systems used to guide street design.

Type	System	Place	How streets are classified: By transportation context	How streets are classified: By environmental context	How streets are classified: By place context	How the classification system informs street design: Recommends specific design elements	How the classification system informs street design: Sets assessment criteria for the movement function	How the classification system informs street design: Sets assessment criteria for the environment function	How the classification system informs street design: Sets assessment criteria for the place function
Conventional classification frameworks	American Association of State Highway and Transportation Officials (AASHTO) (2001)	n/a	✓			✓			
	City of Toronto (2013)	Toronto, Ontario	✓			✓			
	Federal Highway Administration (FHWA) (2013)	n/a	✓			✓			
Complete street classification frameworks	City of Boston (2013)	Boston, Massachusetts	✓		✓	✓			
	City of Calgary (2014)	Calgary, Alberta	✓		✓	✓	✓		
	City of Chicago (2013)	Chicago, Illinois	✓			✓			
	City of Dallas (2016)	Dallas, Texas	✓		✓	✓			
	City of Davis (2013)	Davis, California	✓			✓			
	City of New Haven (2010)	New Haven, Connecticut	✓			✓			
	City of Philadelphia (2012)	Philadelphia, Pennsylvania	✓		✓	✓			
	Kala and Martin (2015)	Jeddah, Saudi Arabia	✓		✓	✓			
	Kingsbury et al. (2011)	Moscow, Idaho	✓		✓		✓		
Other context-sensitive frameworks	Institute of Transportation Engineers (ITE) (2010)	n/a	✓		✓	✓			
	Jones and Boujenko (2009)	London, United Kingdom	✓		✓		✓	✓	✓

Road classification systems are conventionally used to design efficient road networks for vehicles based on segment trade-offs between vehicle mobility and property access/egress (AASHTO, 2001; FHWA, 2013). All classification systems in Table 1 primarily account for transportation context via the vehicle road hierarchy (e.g. differentiation between local, collector, and arterial roads). The motor vehicle road hierarchy is determined by the characteristics of vehicles on the road, such as vehicle volume, intersection spacing, vehicle speed, and average trip length. Non-automobile traffic characteristics, such as the presence and accommodation of pedestrians, cyclists, and transit, could also be considered when classifying streets by transportation context (City of Chicago, 2013; City of Philadelphia, 2012; City of Toronto, 2013; ITE, 2010), but in practice conventional street classification systems only consider the motor vehicle road hierarchy (McCann, 2013). Non-vehicle aspects of transportation context are generally minimal in road classification because road design has historically focused on designing for automobiles before all other users (Hess, 2009; McCann, 2013).

Applying place context is necessary to enrich understanding of a road's character and social utility (Marshall, 2005). Place context can be determined by adjacent land use (City of Boston, 2013; City of Calgary, 2014; City of Dallas, 2016; City of Philadelphia, 2012; ITE, 2010; Kala & Martin, 2015), proximity to commercial and community hubs (ITE, 2010; Kingsbury et al., 2011), or focus group input (Jones & Boujenko, 2009; Kingsbury et al., 2011). All of these examples of place context can be effective ways of describing how a street is used by a community.

None of the classification system in Table 1 use environmental context to identify areas requiring special attention to environmental impacts. It is important to consider the environmental context of the street to recognise that some streets have special environmental needs. For example, a street may run close to an environmentally sensitive area, which requires special attention to water quality impacts of the street, or an area with many pedestrians and cyclists, which requires special attention to the air quality impacts of the street. Accounting for the environmental context of streets in a classification system enriches an understanding of the diverse range of needs of different types of streets.

It is also important to go beyond the conventional vehicle-based classification system when determining the needs of a complete street. In addition to accounting for non-vehicle modes of travel in the determination of transportation context, place context and environmental context should also be considered when identifying the priorities and target performance levels for a given street. Complete street classification systems that only classify streets according to transportation context (for example, those used by Chicago, Davis, and New Haven) are inadequate for describing the community usage patterns of a street, particularly those of non-drivers. Classification systems that use both transportation and place context are fairly common in complete streets policy and literature, and offer a fairly comprehensive way of summarising the usage patterns of different types of streets. Even these frameworks, however, remain incomplete because they do not consider the environmental context of the street.

Setting context-sensitive priorities and objectives

It was observed that the street classification systems in Table 1 inform street design in the following ways:

- By describing desired characteristics of a street of a given classification (e.g. type of facilities, size of these facilities) and
- By setting target performance levels for the street's different functions.

Table 1 summarises how the street classification systems guide street design: whether or not each classification system recommends certain design elements for a street, or sets the performance standards for the movement function, the environment function, and the place function of the street.

Street classification systems are not usually designed as street assessment tools: conventionally, they are used to plan vehicle travel networks. Operational or design characteristics are recommended for different street types so that individual segments can be designed to serve vehicle mobility and property access/egress at levels appropriate to the segment's place in the vehicle road hierarchy (AASHTO, 2001; FHWA, 2013). Similarly, most of the classification systems in Table 1 are only used to recommend the desired characteristics of a street of a given classification, by specifying facility widths, or whether certain elements (e.g. bicycle lane, transit-only lane) should be present. These systems do not offer any guidance for measuring the extent to which a street satisfies its design guidelines, and thus are not suitable for assessing proposed or existing complete streets designs.

Three of the classification systems in Table 1 define completeness for different types of streets by setting context-sensitive design priorities and performance objectives.

The City of Calgary (2014) proposes defining completeness by determining whether a street contains facilities that accommodate pedestrian, cyclist, transit, auto, and goods movement at adequate levels. The quality of a facility for each mode is rated from 0 to 100. The score for each mode is weighted by the relative importance of that mode, which is determined by the street's classification. A street is considered "complete" if its total score is 70 or greater.

However assessing completeness by conformation to geometric guidelines, may exclude some uncommon, but no less adequate road designs. The City of Calgary also does not consider environmental-based or place-based performance criteria in its assessment of streets.

Kingsbury et al. (2011) and Jones and Boujenko (2009) come closest to developing frameworks that comprehensively define the quantitative priorities of a street according to its context. Both of their frameworks use non-form-based criteria in assessing street performance, and characterise street priorities using transportation and place context.

Kingsbury et al.'s (2011) classification system defines completeness for different types of streets by setting target levels of accommodation for the automobile, transit, cyclist, and pedestrian modes of travel. Audited levels of accommodation are compared to the desired levels of accommodation, which are determined by the street classification. This approach is an elegant and comprehensive method of describing how different modes are prioritised on different types of streets. However, their approach could be augmented by classifying streets with regard to environmental context in addition to place and transportation context, and extending the framework to incorporate measures of fulfilment of the environmental and place functions.

Jones and Boujenko's (2009) methodology was the only framework studied that addresses the fulfilment of aspects of all three of the movement, environment, and place functions of the street. For each type of street, desired performance levels are established for a set of 11 design priorities: road safety, environment, pedestrian movement, urban realm, parking, loading, accessibility, freight movement, cyclist movement, transit movement, and general traffic movement. The other methodologies studied focus on adherence to geometric guidelines or movement-related performance standards for the street, which neglects the environmental and place functions. However, Jones and Boujenko's methodology could be improved through consideration of environmental context when setting performance criteria and priorities for different types of streets.

Finally, Jones and Boujenko and Kingsbury et al. both classify their streets in a two-dimensional system according to the level of importance of place and transportation of the street. However, this leads to some unused street classifications (e.g. a street with local-level transport importance and national-level place importance is unlikely to exist). Furthermore, this classification system may not reflect distinctions of land use, expected users, and activity types. For example, a street with moderate transport importance and low place importance might be a suburban collector or an industrial collector, but an industrial collector is more likely to require accommodation of the freight mode while the suburban collector is more likely to require accommodation of the bicycle mode. A more nuanced classification system like that used by the City of Calgary or the City of Dallas, where place context is described by adjoining types of land use instead of generic levels of place importance would better summarise the character of the street and guide how the competing priorities of transportation, environment, and place can be resolved.

Recommended elements of a complete streets assessment framework

From the review of existing street classification frameworks used to inform street design, the following components of a framework with which to measure the completeness of streets are recommended.

First, any tool developed to assess the design of a complete street should use context-sensitive priorities and performance standards to describe different types of streets. A road in an environmentally sensitive area would have a greater weight on environmental performance. Performance standards for an expressway, emphasising vehicle movement, would not be appropriate for a local neighbourhood road. A framework used to assess the design of a complete street should recognise that the transportation, place, and environmental context of a street will affect its priorities and performance standards.

Similarly, a street has transportation, environmental, and place impacts. Thus an assessment framework should set target performance levels for the fulfilment of all of the movement, environment, and place functions in a complete street designs.

Thirdly, any definition of completeness should recognise that there may be many designs for which a street can fulfil its different functions. Specifying that a street must include certain elements of a certain size does not recognise that there may be multiple ways for a street to be "complete", and does not account for the unique character or usage patterns that a street may have. The most flexible metrics are those that recognise varying levels of performance by a street and are versatile enough to measure the performance of a wide range of potential designs of a street.

We recognise that it is a difficult process to assign weights for the different functions of a street. It is unlikely that consensus on what constitutes a universal measure of completeness can ever be obtained. However, the status quo of the complete street design process is inherently qualitative and subjective. A quantitative complete streets assessment framework – even if incomplete – would complement the holistic design techniques already in place by facilitating meaningful discussion of the quantitative trade-offs and design priorities in street design.

Measuring completeness

Many cities in North America consider the complete street philosophy in their planning documents, but few attempt to quantify the performance of a complete street (National Complete Streets Coalition, 2016). Common municipal performance metrics for complete streets can be categorised into three categories: facility-based measures, infrastructure evaluation measures, and outcome measures (Cross County Connection Transportation Management Association, 2011). Examples of performance metrics that fall into each category are summarised in Table 2.

Not all performance measures used by municipalities are suitable for assessing a complete street design. Network-wide facility-based measures and outcome measures are valuable in evaluating the impact of complete street policy on overall health and safety in a city, but are less suitable for evaluating the design of individual streets. Site-focused infrastructure evaluation measures and outcome measures are more useful when assessing the design of individual streets.

When assessing completeness, the levels of performance must be measured for the different functions of the street. The state of practice in assessing the most prominent impacts of a street, as identified in design and the literature, are summarised in Table 3. The impacts are organised into three categories, as suggested by Rodriguez-Valencia (2014b): as part of the fulfilment of the movement function, the environment function, or the place function.

The movement function

Most quantitative assessment of the movement function by street designers is done by calculating the LOS for different modes in a facility. LOS is a term that describes the

Table 2. Examples of complete streets performance measures used by municipalities.

	Facility-based measures	Infrastructure evaluation measures	Outcome measures
Description	Assess the quantity of new facilities	Use consistent criteria to evaluate the quality of a facility	Before-and-after comparison of performance metrics
Examples	• Total new miles of onstreet bicycle routes • Number of new curb ramps • Size of city's green canopy • Number of destinations within a quarter mile	• Highway Capacity Manual 2010 multimodal level-of-service • Pedestrian Environmental Quality Index • Bicycle Environmental Quality Index	• Change in vehicle miles travelled per capita • Percentage of service population within a quarter mile of bicycle facilities • Percent of service population within a quarter mile of transit facilities • Reduction of traffic-related fatalities • Reduction of traffic-related injuries • Change in commuter mode shares

Table 3. Summary of state of practice in assessing the different functions of a complete street.

Function	Characteristic	Description	Assessment procedure	Has been studied specifically in context of complete streets?	Challenges in assessing this function on complete streets
Movement	User-perceived quality of movement LOS	• Street design affects the quality of movement through a facility, by improving user comfort or throughput • Dowling et al. (2008), and NRC and TRB (2010)	• There are many methods available with which to measure or predict LOS for different modes	Yes: Lovas et al. (2015) and Carter et al. (2013)	• It is unclear which techniques are most appropriate for different applications
	Safety	• Physical elements, or changes in design volumes as a result of project implementation, will affect the collision frequency on a street (Harwood et al., 2007)	• Collisions frequency can be measured *in situ*, or estimated using the HSM (NRC (U.S.) et al., 2010)	Yes: Barua et al. (2014)	• Collision frequency estimation using the HSM is not accurate for complex, multimodal facilities (Barua et al., 2014)
Environment	Air quality	• Changes in vehicle volumes and movement patterns have effects on the quantity of vehicle emissions. Emission from a street are affected by the vehicle fleet composition, vehicle operating characteristics, and terrain (Misra, Roorda, & MacLean, 2013) • A complete streets design may not necessarily improve air quality (Peiravian & Derrible, 2014)	• Emission outputs can be modelled using vehicle movement profiles and volumes (Misra et al., 2013) • Air quality impacts can be reported as raw measurements/model outputs, or considered in terms of their health and economic impacts (Litman, 2015; Litman & Doherty, 2009)	Yes: Peiravian and Derrible (2014)	• Accurate estimates in air quality impacts of a street rely on accurate estimates of user volumes of the street for all modes
Environment (continued)	Life cycle impact	• Different types of building materials and construction practices have different levels of energy consumption	• The carbon cost of transporting and installing asphalt, concrete, and aggregate, and the carbon benefit of trees can be calculated for a project (Rodriguez-Valencia, 2014a)	Yes: Rodriguez-Valencia (2014a)	• Rodriguez-Valencia's study (2014a) only addressed new construction. In areas with existing developments, the life cycle costs of removing the existing street prior to new construction must also be considered

(*Continued*)

Table 3. Continued.

Function	Characteristic	Description	Assessment procedure	Has been studied specifically in context of complete streets?	Challenges in assessing this function on complete streets
	Water quality	• Different types of surface materials incur different levels of surface runoff • Complete streets can incorporate stormwater management techniques. For example, bioswales in central medians on urban roads, and ditching and swales on rural and suburban roads (York Region, 2013). Runoff from exclusive pedestrian and bicycle facilities can be treated with low-impact development solutions such as bio-retention soil mixes (Martin, 2016)	• The impacts of low-impact urban stormwater management have been estimated with simulations (Elliott & Trowsdale, 2007; Joksimovic & Alam, 2014; Zimmer, Heathcote, Whiteley, & Schroter, 2007)	No	• The impact of micro-level stormwater management strategies on water quality is difficult to calculate, and, in practice, neglected by municipalities. Stormwater management calculation procedures in Ontario municipalities are only intended for large development areas (Ontario Ministry of Transportation, 2009) • It is uncertain if current stormwater models are sufficiently sensitive for use on alternative complete streets designs • It is difficult to measure the water quality impacts of an existing street because the water quality effects of runoff are “diffuse” and “cumulative” (Litman & Doherty, 2009, p. 5.15-3): pollutants may also concentrate in sediments or in the food chain, making it difficult to quantify the effects of street design on water quality
Environment (continued)	Noise pollution	• Changes in vehicle volumes and movement patterns have effects on user-perceived sound levels. Physical elements on the street may affect sound propagation • The design of a street can change the intensity of noise pollution at its source by changing the volume, type, and vehicle movements on the street (Litman & Doherty, 2009) • Complete streets design can also affect the perceived intensity of noise pollution if there are sound barriers in the design, or if there is significant	• Different models can take into account many factors, including vehicle type, volume, speed, pavement types, sound barrier presence, and topography. A good comparison of different traffic noise models was reviewed by Steele (2001)	No	• Traffic noise modelling is a well-established field, but the sensitivity of traffic noise impacts for different complete streets designs has not been studied

		separation between travel lanes (Steele, 2001)			
	Heat island effects	• Urban areas often have elevated temperatures because of absorption of solar radiation by building materials, trapped air between buildings, and reduced surface moisture caused by impermeable surfaces (Voogt, 2014)	• Heat island effects can be measured by satellite, or by sensors located at different heights above the ground (Voogt, 2014)	No	• Heat island effects are difficult to model and may not be very sensitive to different complete street designs because the temperature effects of a street design may be overshadowed by the structure and material of surrounding urban features, as well as regional and meso-scale weather patterns
Place	User health and happiness	• There are relationships between street design and user health (Khan, 2011; Lee, Mama, & Adamus-Leach, 2012), and satisfaction (Dyck, Cardon, Deforche, & De Bourdeaudhuij, 2011; Golant, 2014; Rogers, Halstead, Gardner, & Carlson, 2011)	• User satisfaction can be assessed through surveys (Litman, 2015) • Increases in resident health can be measured by observing increases in walking and cycling activity (Litman, 2015)	No	• Models that definitively link community health and happiness with all the elements of complete street design have not yet been developed
	Economic impacts	• Street design may influence retail performance and land values (Anderson et al., 2015). Individual studies have also established relationships between physical elements of the street and land value, including bicycle lanes (Rowe, 2013) and street trees (Mullaney, Lucke, & Trueman, 2015)	• Retail performance and land values can be measured *in situ* as a surrogate measure of the fulfilment of the place function	Yes: Anderson et al. (2015)	• Relationships of causality between all the physical elements of complete street projects, retail performance, and property value have not yet been united in a single model. Anderson et al. admit that the complete street projects may not have been solely responsible for the observed gains in business performance and employment (2015) • No study to date has tried to assign economic value to improved community health and safety, or increased accessibility and equity for non-drivers and transport disadvantaged people (Litman, 2003)
				No	

(*Continued*)

Table 3. Continued.

Function	Characteristic	Description	Assessment procedure	Has been studied specifically in context of complete streets?	Challenges in assessing this function on complete streets
	Quality of urban realm	• Expert-developed indices have been developed with the intention of evaluating the quality of urban design, in terms of aspects like walkability, design scale (Ewing & Clemente, 2013; Mehta, 2014)	• An audit of the physical elements of a street can be conducted to construct an index of the quality of the urban realm as a public space		• These indices often take into account elements in the public realm that fall outside the scope of street design (e.g. land type, height of adjacent buildings) which may overshadow the effects of variation between different complete street designs

user-perceived quality of movement through a transportation facility. The 2010 Highway Capacity Manual (NRC & TRB, 2010) is the most common tool used to assess level-of-service (LOS). The 2010 Highway Capacity Manual defines the quality of vehicle movement by comparing a facility's best-case operating conditions to its actual operating conditions. A higher LOS is assigned if a street performs closer to ideal conditions, i.e. for faster movement and reduced delay.

However, evaluation of quality of movement for non-vehicle modes of transport frequently extends beyond measuring the efficiency of movement on the facility. Vehicle LOS methodologies primarily focus on measures of mobility and delay (Dowling, NRC (U.S.), & NCHRP, 2008; NRC & TRB, 2010), but the perceived quality of other modes of travel are significantly impacted by factors influencing user comfort and perceived safety, requiring consideration of how a mode is affected by interactions with other modes and its environment on a scale beyond assessment of transportation amenities in isolation.

Consequently it is a difficult problem to balance the needs of different types of users when designing complete streets, as improving service for one mode (e.g. adding more vehicle travel lanes to reduce delay) may inadvertently decrease comfort and consequently LOS for another mode (e.g. pedestrians become more uncomfortable when vehicle travel speeds are higher). Transit LOS methodologies sometimes consider the pedestrian amenities available at or near transit stops (Dowling et al., 2008; Kittelson & Associates, Transit Cooperative Research Program, United States, Transit Development Corporation, & Arup, 2003; NRC & TRB, 2010). Similarly, bicycle level-of-service methodologies can take into account the characteristics of surrounding vehicle traffic (Dowling et al., 2008; Mekuria, Furth, & Nixon, 2012; NRC & TRB, 2010; Sorton & Walsh, 1994) and adjacent types of land use (Harkey, Reinfurt, Knuiman, Stewart, & Sorton, 1998; San Francisco Department of Public Health Environmental Health Section, 2014) in addition to the physical type and dimensions of the present facility. Evaluation of pedestrian quality of movement (walkability) on a street is typically limited to an assessment of a transportation facility's physical attributes and its user flow characteristics (Lo, 2009), as implemented by typical pedestrian LOS methodologies (Dowling, et al., 2008; NRC & TRB, 2010), but walkability is also sensitive to the entire composition of an urban space and the role of the street in the pedestrian network. Urban design qualities outside of the right-of-way, such as proportionality of surrounding buildings and streetscape complexity, are influential in walkability (Ewing & Handy, 2009). Furthermore, it is important to consider the connectivity and compactness of the pedestrian path network as a whole and how well the network integrates with other modes when evaluating walkability on a street (Forsyth, 2015; Southworth, 2005). As a result, many LOS methodologies have been proposed for vehicle, transit, pedestrian, and cyclist modes, respectively, to try and capture these nuances of user perception.

There is no consensus on the "best" LOS methodology, or even the factors that should be incorporated into a LOS methodology for different modes, for application in the assessment of complete streets. Lovas, Nabors, Goughnour, and Rabito (2015), Smart, McCann, and Brozen (2014), and Carter et al. (2013) studied the sensitivity of different LOS models for complete streets applications. A level-of-service model was deemed suitable for multimodal scenarios if it performed "as expected (i.e. the correct direction and magnitude)" (Carter et al., 2013, p. 39), is appropriate for the application (i.e. whether it can be used on intersections or segments, off-road or on-road bicycle paths, etc.) (Lovas et al., 2015; Smart et al., 2014), and is calibrated to accurately reflect user satisfaction (Smart et al., 2014). As there are many different LOS models, the sensitivity of the models must be tested for alternative right-of-way configurations, similar to the procedures undertaken by Carter et al. (2013), to determine whether or not a given LOS model is versatile enough to produce intuitive results for all of its intended applications. Only then can a measure of LOS be incorporated into a context-sensitive framework for assessing the completeness of a complete street.

Another aim of complete streets projects and policies is to improve the safety of a road for all users, regardless of age or ability. Collision frequency is the most common measure of safety in complete streets projects (Anderson et al., 2015). However, collision rates alone do not reveal the mechanisms of safety improvements: in a study of the before-and-after effects of 37 complete streets projects in the United States, Anderson et al. (2015) was unable to identify the specific causes for collision and injury reduction in any case. Collisions may also be underreported in multimodal situations (Loukaitou-Sideris et al., 2014), leading to inaccurate reports of safety improvements on a street. Finally, guidance as to what constitutes acceptable collision frequencies on any given street is slim: zero collisions on a street are ideal, but how can non-zero collision frequencies be interpreted?

Collision rates can also be estimated for different complete streets designs. Currently, the Highway Safety Manual (HSM) (NRC (U.S.), AASHTO, & NCHRP, 2010) is the most comprehensive method of estimating the safety improvements for infrastructure changes. However Barua, El-basyouny, Islam, and Gargoum (2014) concluded that HSM procedures are not mature enough to evaluate alternative complete street designs because reliable crash modification factors (CMFs) encompassing the variety of complete streets design components may not be available. The HSM also recommends using only three or fewer CMFs at a time: this limit is exceeded frequently in practice when evaluating complete streets, due to their complex nature. Thus the use of HSM methods to predict the safety of alternative complete streets designs requires additional research.

Surrogate safety analysis (including conflict analysis) has potential for use in the assessment of complete streets. The main advantage of using surrogate safety analysis is that shorter observation periods are required (NRC (U.S.) et al., 2010). However, as with collision frequency analysis, surrogate safety research focuses on vehicle movements whereas complete streets emphasises designing for multimodal facilities. The application of surrogate safety analysis to complete streets assessment is hindered by unclear definitions of surrogate measures suitable for multimodal facilities, and a lack of performance standards for multimodal facilities.

In conclusion, safety is an important aspect of the fulfilment of the movement function of a road, but is difficult to interpret accurately from collision statistics, and difficult to estimate for proposed complete street designs. Additional analysis is required to determine the best LOS methodology for analysing the completeness of complete streets.

The environment function

Streets have many potential environmental impacts, including life cycle impacts, air quality impacts, heat island effects, noise impacts, and water quality impacts. Most of these can be measured or modelled for an existing street and predicted for proposed street designs, though the quality of predictions depends on the data and modelling software available.

Many of these impacts have not been estimated specifically within the context of complete streets, and are not formally included in complete streets design or evaluation frameworks. Thus the difficulty lies in determining which of the environmental impacts to quantify in designing an assessment framework for complete streets. Not all environmental impacts may be sufficiently important or sufficiently sensitive to different street designs to be worth measuring or modelling. The following aspects must be considered when determining which environmental impacts of the street to analyse:

- Is this type of environmental impact important compared to other types of environmental impact?
- Is the extent of this environmental impact sensitive to the design of this street?
- What are acceptable or desirable levels of this environmental impact for the street?

Ideally, all of the environmental impacts of a street could be quantified and assessed, but the types of impacts that can be analysed are subject to a practitioner's available instrumentation, software, and monetary resources. Furthermore, knowledge of the specific impacts of complete street design on the different environmental impacts of the street is sometimes limited and will not be resolved until specific investigation of these impacts in response to different complete street designs is undertaken. As such, the impacts that can be considered in complete streets assessment must be determined by a practitioner's available resources and the existing knowledge of which impacts are most sensitive to different complete streets configurations.

It is also difficult to determine how to compare and compile the multitude of potential environmental impacts into one index. The environmental impacts can be reported either in terms of raw outputs and subsequently weighted to account for that impact's social, health, and economic impacts, or translated directly into the value of their externalities. For example, air quality could be reported as either the mass of emissions outputted by users on the road, or the dollar value of the emissions' impacts on health, road and vehicle maintenance, and climate change. Both approaches are valid methods of accounting for the externalities posed by different environmental effects, though they can be difficult to reconcile different types of environmental impacts in a single index. However any environmental impacts of a street that can be measured or estimated can still offer valuable insights into complete street design, and any process by which different categories of environmental effects can be compared in a quantitative way is a potential improvement over the qualitative status quo.

The place function

The place function pertains to the use of the street as a destination, rather than as a means of moving between other places. It refers to the ability of a street to support non-travel activities on or adjacent to the street, such as recreation, and vehicle parking, loading, and unloading (Jones & Boujenko, 2009). Rodriguez-Valencia (2014b, p. 7) states that the place function is a site-specific function whose fulfilment "depends very heavily on the surroundings". Thus designing a complete street to fulfil the place function requires understanding the relationships between the street and the buildings and spaces that frame it (Department for Transport, 2007).

There have been no attempts to directly quantify the fulfilment of the place function by streets. Street design may contribute to the success of the street in its role as a destination, though knowledge of how individual elements actually influence the perceived community perception of the street as a "place" is limited. Potential substitutes for quantifiably estimating the fulfilment of the place function of a complete street include measurements of economic impacts of the street in terms of property values and retail performance, and measurements of community health and happiness (Litman, 2015). Although these metrics may not capture the full nuance of the place function, they have proven useful in the past when evaluating the impacts of a complete street project (Anderson et al., 2015).

Alternately, assessment of the place function of a street using indicators developed for evaluation of the urban realm can be useful (Ewing & Clemente, 2013; Mehta, 2014). These indices are calculated using audits of the physical elements present, and can identify uniqueness, inclusiveness, perceived safety, and aesthetic appeal of a public place. However these were not specifically developed for the evaluation of transportation projects, and thus usually include many elements which are out of the scope of complete street projects (e.g. façade quality and variety, adjacent land use types, building height). The effects of these elements may overshadow the effects of the elements that do comprise a complete street project.

It is prudent to make use of any meaningful quantitative indicators of the place function available. However "place" is a complex concept concerning the connections between culture, environment, history, and the individual identity of users on the street (Sepe & Pitt, 2014). The use of quantitative indicators alone may be overly simplistic and lead to inaccurate or incomplete conclusions. Caution should be used when using surrogate measures to evaluate the fulfilment of the place function of a street.

Context-sensitive street assessment

Many different tools are available with which to quantify a street's ability to fulfil its different functions: aspects of fulfilment of a street's movement, environment, and place function can all be quantified for existing streets and proposed street designs.

An additional challenge lies in being able to interpret and combine different metrics in a way that accurately reflects their relative importance for any given street: for example, how can air quality be compared to noise pollution, or cyclist comfort levels compared to pedestrian comfort levels on different kinds of streets? Furthermore, different target performance levels should be set for the different functions of a street: for example, a major arterial in an industrial area will require higher levels of vehicle accommodation than a local neighbourhood street. A context-sensitive approach is needed when evaluating complete streets. Municipalities rarely offer guidance in this regard, where performance goals for individual streets can be established somewhat arbitrarily with reference to baseline data, and where there is little discussion as to how metrics of different priority levels can be combined for interpretation.

A street classification system sensitive to transportation, place, and environmental context can be used to combine individual metrics into a single measure of completeness that reflects how well the design of a street fulfils the movement, environment, and place functions. Performance targets and priorities can be set for the different characteristics of a street to reflect their relative importance on different types of streets. Thus by comparing the performance of an existing or proposed street against the target performance levels of that class of street, the "completeness" of a street can be measured within a context-sensitive framework.

Applications

We recognise that developing a fully context-sensitive complete streets measurement tool is a difficult process and may fall short in spite of best efforts, and that universal consensus about what constitutes "completeness" for different types of streets is impossible. However, even a tool that can partially assess the trade-offs of complete street design has been proven to have valuable applications.

Identifying incompleteness in a network

A measure of completeness can be used to assess the performance of a network as a whole. Many municipalities do assess the citywide impacts of complete streets policy using outcome-based criteria such as collision frequency, sales tax revenue, and transit ridership (Cross County Connection Transportation Management Association, 2011). These metrics, however, do not take into account the heterogeneity of the network, and are meaningless without comparison to the target performance levels of individual streets within the network. A definition of completeness for different types of streets is necessary to characterise desired performance on individual streets in the network.

Assessing the completeness of all the streets in a network yields useful insights as to how to prioritise infrastructure investment and develop planning policy, as has already been proven by Kingsbury et al. (2011) and Jones and Boujenko (2009). Measuring the completeness of all the streets in a network illuminates patterns of "incompleteness" in the network, which could be indicative of poor service for a particular mode in the network, localised areas of transport inequity, or other problems in the network. This information could be used in turn to target neighbourhoods for street improvements or to remedy neglected areas of municipal policy. Jones and Boujenko (2009) used their framework to identify the ways in which streets' performance fall short of their target performance levels in different categories, and used this to identify areas in which to prioritise infrastructure investment and recognise shortfalls in planning policy. Similarly, Kingsbury et al. (2011) use their completeness tool to identify deficiencies for different modes in the entire network of their study area, and to identify patterns for shortfalls in completeness levels.

Solving the right-of-way allocation problem

A novel use of an assessment framework is in solving the right-of-way allocation problem for complete streets. The right-of-way allocation problem is described by Rodriguez-Valencia (2014a) as the optimisation of the distribution of the available land between private plots for the fulfilment of the movement, environmental, and place function of a street.

The allocation of land to different types of facilities can contribute to or hinder the fulfilment of the three functions of the street.

For most municipalities, formal methods of quantitatively solving the right-of-way allocation problem for complete streets are absent or rudimentary (Gregg & Hess, 2016). Municipalities rarely acknowledge that trade-offs must sometimes be made when solving the right-of-way allocation problem. Even when criteria for evaluating alternative street designs are recommended, methods of how different design goals should be prioritised are not specified. For example, the City of Boston recommends using multimodal level-of-service (MMLOS) in assessing different designs but not specify how highly MMLOS should be prioritised when determining the optimal design (City of Boston, 2013). The City of Charlotte explicitly states that the specific method of evaluating the trade-offs should be left open to the plan/design team, as long as the process is documented (City of Charlotte, 2007). In contrast, the City of Dallas (2016) does rank the design priorities for different types of streets, though this framework is only used for qualitative guidance in the street design process, rather than formally outlining how trade-offs can be made in a street design. On the whole, municipal guidelines do not offer a formal structure with which to prioritise the functions of a street in the right-of-way allocation problem.

Most of the frameworks summarised in Table 1 also do not recognise that trade-offs must sometimes be made when solving the right-of-way allocation problem. Frameworks that set minimum and maximum geometries or mandate the type of transportation facilities for inclusion on a street is practical if space is not a limitation. However this design strategy is unhelpful if the right-of-way is insufficient to accommodate all the recommended facilities. Decisions must be made as to which elements to include or exclude in the available space.

The right-of-way allocation problem could be solved by designing a street to maximise its ability to fulfil all of its required functions. The frameworks proposed by Jones and Boujenko (2009), Kingsbury et al. (2011), and the City of Calgary (2014) all set priorities and target performance levels for different categories of streets and measure the degree to which existing streets meet these standards. Measuring the degree to which proposed street designs meet these performance goals could be helpful in determining the optimal design for a complete street. Such a tool would not usurp the qualitative community-driven decision-making processes recommended for complete streets design (National Complete Streets Coalition, 2011), as there may be aspects of a street, tangible or intangible, that are unique and cannot fit within any quantification framework. The degree of conformation to a set of target performance levels should complement, rather than supplant, the holistic nature of complete streets design.

In recognising that there might be no way to fit all the desired elements in the available right-of-way, a framework suitable for solving the right-of-way allocation problem is one that recognises that there are different degrees to which each function of the street can be fulfilled, i.e. the street can be partially complete. The frameworks proposed by Jones and Boujenko (2009), Kingsbury et al. (2011), and the City of Calgary (2014) all acknowledge that a street has levels of completeness beyond conformation or non-conformation to recommended design guidelines. Thus completeness can be calculated for a set of given street designs, and the design that maximises completeness would be a preferred solution to the right-of-way allocation problem.

Conclusion

Complete streets, a design concept intended to shift the focus of road design from optimisation of auto-based performance to consideration of all modes on the street, has admirable goals but lacks quantitative guidance as to how different modes and functions should be prioritised for different streets. A context-sensitive framework with which to quantitatively define the completeness of a complete street by comparing a street's fulfilment of the movement, environmental, and place functions to target levels of performance determined by the street's transportation, environmental, and place context has useful applications in planning and design. However, a framework with all these elements has not been found in design or the literature.

Firstly, assessment criteria for a street should be set in relation to the street's transportation, environment, and place context. In an examination of different street classification frameworks it was observed that streets are always classified according to transportation context and sometimes classified according to place context. Street classification based on environmental context was not observed. The classification frameworks studied were also not comprehensive in evaluating a street's fulfilment of the movement, environmental, and place functions: most frameworks only recommend geometries for design elements on a street, without any method of evaluating existing or proposed street designs. A measure of "completeness" should recognise that a function of a street can be fulfilled in many ways, and many levels in fulfilment beyond compliance or non-compliance.

There are many ways to measure the performance of the street in the dimensions of movement, environment, and place, but not all of these are suitable for inclusion in the complete street design process. The challenge in measuring the fulfilment of the movement function lies in determining which of the many available models to use: a sensitivity analysis is required to determine if a model is sufficiently sensitive to the elements of interest on the street. There are also many models developed for the measurement of the different types of environmental impact of streets, where the challenge lies in determining which of these environmental impacts are sufficiently important and sensitive to the design of a street to be worthwhile for inclusion in the complete street assessment. The place function is more difficult to quantify but user surveys, economic characteristics, and physical audits may be used as a surrogate for evaluating a street's fulfilment of the place function.

It is a difficult task to determine which aspects of a street should be measured and how they should be weighted for different classifications of streets, but a context-sensitive approach to measuring the completeness of streets has been proven to have valuable applications. Assessing the completeness of all the streets in a network would allow municipalities to prioritise streets for infrastructure investments, and to develop strategies for policy development by identifying and targeting patterns of incompleteness in the network. Additional work is required to define the priorities and performance objectives for different types of streets so that the overall completeness of complete streets designs can be assessed. Furthermore, the ability to assess the completeness of existing and proposed streets would be a useful tool with which to solve the right-of-way allocation problem by visualising the quantitative trade-offs associated with the geometries of different street designs. In these cases, even an incomplete assessment tool that can only take classify and assess streets by transportation, environment, and place criteria has utility, though a tool that can incorporate all these considerations into its framework is best.

There is already a wealth of ways with which to quantitatively assess different aspects of a complete street, but context is needed to combine and interpret the available information. Several frameworks for context-sensitive complete street have already developed for complete streets planning and design, but these frameworks lack important elements of complete street classification and assessment: namely classification and evaluation by all three of transportation, environment, and place criteria. Moving forwards and expanding the scope of context-sensitive, quantitative complete street assessments will complement the status quo of predominantly qualitative complete streets evaluation.

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