Measuring the Completeness of Complete Streets

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A tool for measuring the "completeness" of a complete street has applications in developing policy, prioritizing 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 fulfillment 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 community 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.

Keywords: complete streets, context-sensitive design, transportation, place, environment.

Introduction

"Complete streets" are an emerging concept in North American transportation planning and design discourse. They 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 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 the "completeness" of existing or proposed streets. Completeness, in this case, refers to the extent to which a street fulfills its required functions. Such a framework would assist in the effective development of complete streets design and policy.

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, socialization, 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 fulfillment 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 fulfills 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 prioritized are more numerous. Although all complete streets are designed 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). For example, a rural complete street would look different from an urban complete street.

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 of a street and the street's design objectives can be formalized 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 summarizes 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. Three (American Association of State Highway and Transportation Officials, 2001; City of Toronto, 2013; Federal Highway Administration, 2013) are examples of how conventional street classification systems guide street design. Nine (City of Boston, 2013; City of Calgary, 2014; City of Chicago, 2013; City of Dallas, 2016; City of Davis, 2013; City of New Haven, 2010; City of Philadelphia Mayor's Office of Transportation and Utilities, 2012; Kala & Martin, 2015; Kingsbury, Lowry, & Dixon, 2011) 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 (Institute of Transportation Engineers, 2010; Jones & Boujenko, 2009) were also selected as supplementary examples of the use of context-sensitive frameworks in street design.

[Table 1 near here.]

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 community 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 maximizing positive environmental impacts and minimizing negative environmental impacts in the design of a street. Community context describes the significance of a street to its users as a social or recreational destination.

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 (American Association of State Highway and Transportation Officials, 2001; Federal Highway Administration, 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. Nonautomobile 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 Mayor's Office of Transportation and Utilities, 2012; City of Toronto, 2013; Institute of Transportation Engineers, 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 focussed on designing for automobiles before all other users (Hess, 2009; McCann, 2013).

Applying community context is necessary to enrich understanding of a road's character and social utility. Community context can be determined by adjacent types of land use (City of Boston, 2013; City of Calgary, 2014; City of Dallas, 2016; City of Philadelphia Mayor's Office of Transportation and Utilities, 2012; Institute of Transportation Engineers, 2010; Kala & Martin, 2015), proximity to commercial and community hubs (Institute of Transportation Engineers, 2010; Kingsbury et al., 2011), or focus group input (Jones & Boujenko, 2009; Kingsbury et al., 2011). All of these examples of community 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 recognize 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 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, community 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 (e.g. Chicago, Davis, 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 community context are fairly common in complete streets policy and literature, and offer a fairly comprehensive way of summarizing 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 summarizes 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 (American Association of State Highway and Transportation Officials, 2001; Federal Highway Administration, 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.

Kingsbury, Lowry, and Dixon'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 framework could also be extended to incorporate measures of fulfilment of the environmental and place functions.

Jones and Boujenko's (2009) technique goes a step further. For each type of street, desired performance levels are set for a set of eleven design priorities: road safety, environment, pedestrian movement, urban realm, parking, loading, accessibility, freight movement, cyclist movement, transit movement, and general traffic movement.

Finally, 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 0-100. 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, these three assessment frameworks may not be flexible enough to account for the many potential configurations of a street. The City of Calgary (2014) assesses completeness by conformation to geometric guidelines, which may exclude some uncommon, but no less adequate road designs. Kingsbury et al. (2011) and Jones and Boujenko (2009) do not provide details of how their streets are audited in their studies.

Jones and Boujenko's (2009) methodology was the only framework studied that addresses the fulfillment of aspects of all three of the movement, environment, and place functions of the street. The other methodologies focus on setting design guidelines or movement-related performance standards for the street, which neglects the environmental and place functions.

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, emphasizing vehicle movement, would not be appropriate for a local neighbourhood road. A framework used to assess the design of a complete street should recognize that the transportation, community, 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 fulfillment of all of the movement, environment, and place functions in a complete street designs.

Thirdly, any definition of completeness should recognize that there may be many designs for which a street can fulfill its different functions. Specifying that a street must include certain elements of a certain size does not recognize 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 recognize 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.

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 categorized 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 summarized in Table 2.

[Table 2 near here.]

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-focussed 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 summarized in Table 3. The impacts are organized into three categories, as suggested by Rodriguez-Valencia (2014b): as part of the fulfillment of the movement function, the environment function, or the place function.

[Table 3 near here.]

The Movement Function

Most quantitative assessment of the movement function by street designers is done by calculating the level-of-service for different modes in a facility. Level-of-service is a term that describes the user-perceived quality of movement through a transportation facility. The 2010 Highway Capacity Manual (National Research Council (U.S.) & Transportation Research Board, 2010) is the most common tool used to assess level-of-service. 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, user-perceived quality of movement through a transportation facility can extend beyond efficiency of movement and minimizing delays, particularly for non-vehicle modes of transport. As many potential variables can affect user-perceived level-of-service, many level-of-service methodologies have been developed for the vehicle, transit, pedestrian, and cyclist modes.

There is no consensus on the “best” level-of-service methodology for a mode. Lovas et al. (2015), Smart et al. (2014), and Carter et al. (2013) studied different level-of-service models in 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 level-of-service 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 level-of-service model is versatile enough to produce intuitive results for all of its intended applications. Only then can a measure of level-of-service 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 (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) (National Research Council (U.S.), American Association of State Highway and Transportation Officials, & National Cooperative Highway Research Program, 2010) is the most comprehensive method of estimating the safety improvements for infrastructure changes. However Barua et al. (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 (National Research Council (U.S.) et al., 2010). However, as with collision frequency analysis, surrogate safety research focusses on vehicle movements whereas complete streets emphasizes 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 level-of-service methodology for analyzing 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 analyze:

- 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?

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 fulfillment “depends very heavily on the surroundings.” Thus designing a complete street to fulfill 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 fulfillment 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 fulfillment 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).

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). Using economic impacts or community health and happiness to measure the placemaking ability of a street may be overly simplistic and lead to inaccurate or incomplete conclusions. Caution should be used when using surrogate measures to evaluate the fulfillment 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 fulfill its different functions: aspects of fulfillment of a street’s movement, environment, and place function can all be quantified for existing streets and proposed street designs. A 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 can be combined for interpretation.

A street classification system sensitive to transportation, community, 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 fulfills 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

Solving the Right-of-Way Allocation Problem

The right-of-way allocation problem is described by Rodriguez-Valencia (2014a) as the optimization of the distribution of the available land between private plots for the fulfillment 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 fulfillment 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 prioritized are not specified. For example, the City of Boston recommends using multimodal level-of-service in assessing different designs but not specify how highly MMLOS should be prioritized 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 prioritize the functions of a street in the right-of-way allocation problem.

Most of the frameworks summarized in Table 1 also do not recognize 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 maximize its ability to fulfill 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 recognizing 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 recognizes 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 maximizes completeness would be a preferred solution to the right-of-way allocation problem.

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 characterize desired performance on individual streets in the network.

Assessing the completeness of all the streets in a network can yield useful insights as to how to prioritize infrastructure investment and develop planning policy. Measuring the completeness of all the streets in a network can illuminate patterns of “incompleteness” in the network, which could be indicative of poor service for a particular mode in the network, localized 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 prioritize infrastructure investment and recognize 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.

Conclusion

A context-sensitive framework with which to quantitatively define the completeness of a complete street according to transportation, environment, and place-based criteria has not been found in design or in the literature. A framework could define the completeness of a street by comparing a street’s fulfillment of the movement, environmental, and place functions to target levels of performance determined by the street’s transportation, environmental, and community 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 community context. Street classification based on environmental context was not observed. The classification frameworks studied were not comprehensive in evaluating a street's fulfillment 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 recognize that a function of a street can be fulfilled in many ways, and many levels in fulfillment 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 fulfillment 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 and economic characteristics may be used as a surrogate for evaluating a street's fulfilment of the place function.

A context-sensitive approach to measuring the completeness of streets has several potential applications. Assessing the completeness of existing and proposed streets would be a useful tool with which to solve the right-of-way allocation problem: a solution to the right-of-way allocation problem would be the one that maximizes the street's completeness. Assessing the completeness of all the streets in a network also allows municipalities to prioritize 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.

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Tables

Table 1. Street Classification Systems Used to Guide Street Design.

			How streets are classified			**How the classification system informs street design**			
Type	**System**	**Place**	**By transportation context**	**By environmental context**	**By community context**	**Recommends specific design elements**	**Sets assessment criteria for the movement function**	**Sets assessment criteria for the environment function**	**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	✓		✓		✓		

			How streets are classified			How the classification system informs street design			
Type	**System**	**Place**	**By transportation context**	**By environmental context**	**By community context**	**Recommends specific design elements**	**Sets assessment criteria for the movement function**	**Sets assessment criteria for the environment function**	**Sets assessment criteria for the place function**
Other context-sensitive frameworks	Institute of Transportation Engineers (ITE) (2010)	n/a	✓		✓	✓			
	Jones and Boujenko (2009)	London, United Kingdom	✓		✓		✓	✓	✓

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 (level-of-service)	• Street design affects the quality of movement through a facility, by improving user comfort or throughput (Dowling, National Research Council (U.S.), & National Cooperative Highway Research Program, 2008; National Research Council (U.S.) & Transportation Research Board, 2010)	• There are many methods are available with which to measure or predict level-of-service 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 Highway Safety Manual (National Research Council (U.S.) et al., 2010).	Yes: Barua et al. (2014)	• Collision frequency estimation using the Highway Safety Manual 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).	Yes: Peiravian & Derrible (2014)	• Accurate estimates in air quality impacts of a street rely on accurate estimates of user volumes of the street for all modes.

Function	Characteristic	Description	Assessment procedure	Has been studied specifically in context of complete streets?	Challenges in assessing this function on complete streets
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.

Function	Characteristic	Description	Assessment procedure	Has been studied specifically in context of complete streets?	Challenges in assessing this function on complete streets
Environment (continued)	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 precise quantity 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.

Function	Characteristic	Description	Assessment procedure	Has been studied specifically in context of complete streets?	Challenges in assessing this function on complete streets
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 separation between travel lanes (Steele, 2001).	• 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.
	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.

Function	Characteristic	Description	Assessment procedure	Has been studied specifically in context of complete streets?	Challenges in assessing this function on complete streets
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).	• Residents on streets can be surveyed and then quantified in terms such as "percentage of satisfied residents" as a surrogate measure of the fulfillment of the place function (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.

Function	Characteristic	Description	Assessment procedure	Has been studied specifically in context of complete streets?	Challenges in assessing this function on complete streets
Place (continued)	Economic impacts	• Street design may influence retail performance and land values (Anderson et al., 2015). Individual studies have also established relationships between 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 fulfillment of the place function.	Yes: Anderson (2015)	• Specific relationships of causality between the physical elements of complete street projects have not been united in a single model to predict changes in retail performance and property value. Anderson et al. admit that the street projects may not have been solely responsible for the gains in business performance and employment (2015). • No study to date has tried to assign economic value to improved community health and safety, and increased accessibility and equity for non-drivers and transport disadvantaged people (Litman, 2003).