Narrower Lanes, Safer Streets

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Abstract: Of all street design elements, no other has evoked as much bafflement, incredulity and conjecture as the safer range of travel lane width. Traditional traffic engineers argue wider lanes are safer. Supporters of the livable street concept passionately promote the safety benefits of a relatively narrower lane width. Recent claims are emerging in favour of the livable street approach. However, neither side has yet produced any empirical evidence that links crash frequency or severity to lane width. This paper attempts to address this disquieting quandary. Extensive literature review, both academic and project reports or articles, has been conducted to examine recent claims and outline an emerging scientific perspective, and to provide an important logical platform for this research. In order to examine a relationship between lane width and crash rates, this study utilized two existing crash databases from Tokyo and Toronto, originally collected as part of greater effort to investigate the occurrence mechanism for vehicle-to-vehicle side-impact crashes at signalized intersections. Five novel but identical evidences are discovered for both cities. Both narrow (less than 2.8m) and wide (over 3.1~3.2m) lanes have proven to increase crash risks with equal magnitude. Safety benefits bottom out around 3.1m (for Tokyo) and 3.2m (for Toronto). Beyond the "safety valley curve", wider lanes (wider than 3.3m) adversely affect overall side-impact collisions. Secondly, among the types of crashes, right-turn crashes are relatively sensitive to lane width, while the safer range of lane width is relatively narrower for right-angle and left-turn crashes. Thirdly, the lateral displacement of driving maneuvers or oscillations stays within a narrow range (0.2m from bottom of safety curve), implying that humans display a surprisingly narrow "safety comfort zone" while trying to achieve a dynamic equilibrium status within the travel lane width. Fourthly, the capacity of narrower lanes is higher. No difference on safety and large vehicle carrying capacity is observed between narrower and wider lanes. Pedestrian volume declines as lanes widen, and intersections with narrower lanes provide the highest capacity for bicycles. Finally, wider lanes (over 3.3~3.4m), the predominant practice of Toronto regions, are associated with 33% higher impact speed rates and higher crash rates, despite higher traffic volumes and one-sixth the population than that of Tokyo. Given that the empirical evidence favours 'narrower is safer', the 'wider is safer' approach based on personal or intuitional opinion should be discarded once and for all. The findings acknowledge human behavior is impacted by the street environment, and narrower lanes in urban areas result in less aggressive driving and more ability to slow or stop a vehicle over a short distance to avoid collision. Designers of streets can utilize the "unused space" to provide an enhanced public realm, including cycling facilities and wider sidewalks, or to save money on the asphalt not used by motorists.

INTRODUCTION

Of all the street design elements, no other has evoked as much bafflement, incredulity and conjecture as the safer range of travel lane width. The width of travel lane is the fundamental building block of street design and one of the important elements of public space allocation for all urban streets. With the growing popularity of the livable street concept, the topic of lane width safety continues to generate intense debate among transportation practitioners. Traditional traffic engineers argue a wider lane is safer. Although every engineering standard publication (FHWA 2011; TAC 1999) identifies pavement width as the most influential safety feature, discussion is surprisingly scarce (Hauer, 1999) on what research says about the nature of the relationship between lane width and crash frequency or severity. To the contrary, the supporters of livable streets passionately promote the safety benefits of a relatively narrower lane width (Parsons B. Group, 2003; Pein 2003; Longenbaker and Furth, 2008; Navazo, 2009; Miller 2009; Petritsch, 2010; and Speck, 2014). New evidences and project-based claims are emerging in favour of the latter approach. In addition, recent upgrades of transportation standards are more favourable towards narrower travel lanes (3.0 m wide) in urban street networks (ITE 2008, ITE, 2010, NACTO, 2014, and City of Toronto 2015).

With neither side yet to produce any direct empirical evidence linking crash frequency or severity with lane width, this paper attempts to address this disquieting quandary.

A common approach to settle any safety debate is not an easy task. Faced with economic, political and environmental challenges however, the question of appropriate infrastructure sizes and design scales is critical to sustainable growth in urban areas. Equitable proportional reallocation of public space based on efficiency of transport modes is emerging as a central strategy among multimodal practitioners. Growing scientific evidence in support of limiting design elements to human scale is also aligning with livable street principles, strongly suggesting avoiding overdesign to minimize negative street safety outcomes.

The lane width debate unfolds in several layers. Firstly, many conventional engineers firmly believe that concern for safety is implicit in matters, and engineering standards will automatically ensure a proper amount of safety is built into roads. The mere existence of scientific research of safety effects on lane width raises serious doubts to this belief (Hauer, 2007; Dumbaugh 2009; Milton 2012; Speck, 2014). Secondly, the adjustment of human adaptation behaviour (generally known as the Peltzman effect) in response to street geometry - in this case narrower or wider lane width - interjects further confusion to lane width safety debate (Specht, 2007). Finally, there is no clear point of safety failure in the lane width debate, as it is commonly observed in other fields of Civil Engineering such as the collapse of a bridge or building (Hauer, 2007).

In order to gain a deeper understanding of lane width and safety relationship, this paper summarizes the findings of relevant literature underlying the safety concept of lane width. These findings demonstrate that the path to safer and compact streets is a narrower lane. Despite the “conventional wisdom” claiming narrower lanes result in higher crash frequencies, the research studies generally conclude one of two things: the effect of lane width on safety is not conclusive or wider lanes (more than 3.4m) are actually detrimental to safety (Noland, 2002; Potts et. al. 2007; Sinclair K.M., 2011; and Hauer 2012).

In this paper, three basic principles, regardless of variation in research approach, guide to establish acceptable solutions for the safer lane width debate’s stakeholders. Firstly, all significant questions require quantitative answers. In this paper, a quantitative approach to the nature of lane width and collision frequency is presented in the context of human adaptation and their response to geometric elements and the street or surrounding environment. Secondly, the approach is to identify safety failure as a “matter of degree”, not a “matter of either - or” Hauer (1999). Risks of injury are highly non-linear (Elvik, 2009). Risks are not constant. This research identifies the non-linear shape of the relationship between collision frequency and lane width while defining the boundary of “safer or unsafe zone”, instead of failure point. Thirdly, this analysis avoids a common pitfall of previous studies which generally select a functional form that never reaches a ‘bottom’. A detail examination by Hauer (2012) on lane width and safety provides a foundation to this research. While crash rates decrease as lane width increases upto certain width, the relationship between lane width and crash experience is non-linear, with optimal safer range of lane width bottoming out when it crosses a boundary limit (such as, widening lanes beyond 12 ft or 3.6m may be detrimental to safety).

This study examines if there exists a relationship between lane width and crash rates, using data obtained from Tokyo and Toronto, as part of a larger safety analysis at signalized intersections in urban areas.

NEED FOR SAFETY EVALUATION OF LANE WIDTH

Wider lane widths are often thought to provide extra safety margins in a traditional street design paradigm. Although this assumption may be partially valid in high-speed and high-capacity expressway/highway conditions, in an urban commuting environment the need for a safety margin is smaller due to fewer trucks, lower speeds and higher interaction between the street users. By narrowing existing wide lanes based on “highway” standards, more capacity can be obtained for pedestrians, bicycles and transit vehicles and users. The increased probability of walking and cycling then paves the way for a “safety in numbers” condition that further reduces collision rates for all transportation modes sharing the street space.

The ripple effects of carefully designed narrower streets are large (Kenneth and Chen, 2012). Combined with other safer design features (such as a planted median, bump-outs or bulb-outs), narrower lanes in off-peak periods act as defacto psychological design controls, inducing the maintenance of a safer range of vehicle operating speeds. Predominantly in the central business districts, where the ratio of non-automobile to vehicle flow is significant, the benefits of narrower lanes combined with elimination of unwarranted slip lanes is accentuated. Consistent speeds help to reduce risks to vulnerable users. In addition, shorter pedestrian crossings mean shorter signal cycles to reduce vehicle delay.

Figure 1 illustrates an example of a very wide lane (5.5m) that leaves extremely narrow and substandard boulevard space (nearly 2.0m) in front of a heavily used subway entrance. Extra widths attract illegal driving activities, including passenger drop-off, delivery stops, taxis waiting, and undefined right-turn movements. These illegal activities result in collision rates seven times higher than the heavy right-turning volumes and narrower/appropriate width shared through lane (3.3m) in the westbound direction. This example demonstrates that little or if any knowledge of lane width and crash experiences was considered in the intersection's design.

Although prevailing assumptions of wider lanes providing safer conditions for vehicles, real crash experiences show the exact opposite outcome. Besides inviting higher speeds due to the greater lane width (Fitzpatrick et. al 2001; Fitzpatrick and Schneider 2005), poor design principles based on "conventional wisdom of wider is safer" create vicious cycles that lower the level-of-service for pedestrians and lead to dangerous conditions for all street users.

Figure 1: Example of imbalanced distribution of street space in favour of a very wide travel lane

The enormity of the social and economic burden of crashes is a major barrier to building quality of life for growing urban populations. While congestion costs in Ontario ($3.3~$6.0 billion per year) are frequently promoted as a productivity loss to society, the social cost of collisions exceeded $18 billion per year (Vodden et. al. 2007). The cost of collisions in urban areas of Toronto is over $2 billion (City of Toronto, 2013) a year.

In general nearly half of all collisions occur at intersections. The aging population (+65) is overrepresented in fatal collisions, accounting for 40% of total fatalities in 2013 (Transportation Services, 2013). Pedestrians also carry a heavy burden with total fatalities over 60%. Both community members and practitioners identify wider cross-sections, longer pedestrian crossings, and high-speed turn maneuvering as major causes of these disproportionate and increasing number of fatal and injurious collisions. In addition, generous corner radii and unwarranted right-turning lanes increase risks for vulnerable street users. To reverse the deteriorating safety conditions, evidence based design principles for lane width selection are emerging.

International Practice of Lane Width

An extensive survey of international lane width practices was conducted by Hall et. al (1995) that demonstrates lane width policies fall within a narrow range. Sinclair K.M. (2011) describes some patterns among the international standards, such as: lane-departure crashes being less likely on urban streets; the best use of cross-sections for multimodal safety in low-speed conditions; highways require larger edge distances because drivers tend to shy away from the centerline; extremely narrower lanes (2.5 to 2.9m) are permitted in UK under certain conditions; and, the link-place approach practiced widely in UK, Australia, and New Zealand balances the need for movement and accommodation of destinations.

Factors that Determine Lane Width

Almost every standard-setting guidelines or manual describes different lane width requirements for every road classification, but few describe the factors that determine the appropriate range of lane width (Sinclair K.M., 2011; Hauer 2012; Oregon DOT 2013; Isebrands et. al. 2015; and City of Toronto 2015). The most appropriate lane width will be specific to the circumstances that have been identified in influencing the size of lane widths, including:

1. Vehicle type (large vehicles, transit vehicles, trucks);
2. Vehicle volumes and capacity;
3. Target vehicle speed (design speed, average speed and posted limits) and lateral displacement;
4. Level of pedestrian and bicycle activities and facilities;
5. Provisions for other users;
6. Type and number of lane uses (turning, through, curbside);
7. Emergency vehicle operations;
8. Context (existing or future function of streets and land-uses);
9. Situation adjacent to the lane (delivery, on-street parking, boulevards);
10. Topography and Geometry (continuous median, horizontal alignment, cross fall or slope of the road); and,
11. Other considerations (snow cleaning and storage, topography and road camber or curvature, maintenance, bridges and crossing points, planned changes of streets)

This study investigates the first seven factors as the most critical issues to settling the lane width selection debate.

Geometric Design Policies of Lane Width

It is generally agreed upon among leading safety practitioners that the standards for *road width, particularly lane width policies*, adopted by many engineering guidelines, appear to be scientifically unreliable, and based on completely contradictory safety principles. In a comprehensive review of geometric standards, Hauer (1999) emphasizes the historical roots of the lane width standards, going back to the period of the 1940s, when geometric design policies were developed despite the lack of information on crash frequency or severity. He identified Taragin's work (1944) as the single reference for all lane width policies used by standard-setting institutions despite the paper containing no information about lane width crash frequency or severity. An older study, known as Belmont's data (1954), indicates that making carriageways wider than 22 ft (6.7m) for two-lane roads is detrimental to safety. Historical roots of lane width assumptions that undermine the current debate however, go back to the early part of the 20th century. Historical evidence on urban street design suggests that the current practice of a 10 m or 11m wide collector or minor two-lane arterial roadway is based on the standards for horse carriages used during the 1920s (Friedman, 2010). Surprisingly, these standards are still used today by road design practitioners in North America.

Older studies predominantly focused on rural roads. One of them starting to doubt the significance of pavement widening for safety benefits (Raff, 1953). Several recent studies have been conducted relating lane width and actual crashes, with researchers finding an increase in crash rate for lane-widths wider than 11 ft (3.3m) on two lane roads (Gross et. al. 2009; Harwood et. al. 2000; Fildes et. al. 1987; Zegeer et. al., 1980 and 1981, McLean, 1980). Using a driving simulator of two configurations of lane widths (3.5 m and 3m) on rural roads, a French study demonstrated that reducing the lane width had no impact on speeds, but induced drivers to drive closer to the centre of the road (Rosey et. al. 2009). Consistent findings from these researches have shown that there is no evidence that supports the assumption that road safety is increased with wider traffic lanes. These findings did not however give pause to standard-setting organizations overstating the benefits of wider lane widths.

The urban traffic environment is more complex than the linear world of un-interactive highway movement. Recent lane width related studies have thus focused on urban streets, particularly arterials and collector streets. A review of available research on this issue in urban areas conducted by Potts et al. (2007) found no general indication that the use of lanes narrower than 3.6 m on urban and suburban arterials increased crash frequencies. Using complete streets projects and background review, Nebraska's Department of Road also concluded that narrow lanes are not necessarily correlated with increased crash risk in urban and suburban areas (Hansen at. el. 2013). A similar review conducted by Dumbaugh and Rae (2009) found that road widening occurs at the expense of safety, reporting that the safety benefit of widening lanes stops once lanes reach a width of roughly 11 feet (3.4m), with crash frequencies increasing as lanes approach or exceed 12-foot (3.7m).

To determine the impact of certain road infrastructure, Noland (2002) found that lanes 12 ft (3.7m) wide or more on collectors were the only category linked to a significant increase in the number of fatalities compared to narrower lanes. Wider lanes attract speeding behavior. Several studies found the root cause of excessive operating speed (Fitzpatrick et al., 2001; Poch and Mannering, 1996; Farouki and Nixon, 1976), since higher speed vehicles need bigger gaps, and the greater the width available the greater the vehicle speed. In light of this widely-held consensus among researchers, Noland concluded "it is in general, not possible to support the engineering hypotheses (the "conventional wisdom" that a wider lane is a safer lane).

Change in Practice to Safety Principles

In the last decade, several leading safety manuals have adopted profound changes in their safety principles (Highway Safety Manual, 2010). Hauer advocated that "substantive safety" was more appropriate for addressing crashes than "nominal safety", that which generally assumes the application of a design standard provided safety (Milton 2012). More recently, a planning focused safety approach has emerged. Instead of a traditional "reactive approach" that identifies "black spots" at high cost existing communities, practitioners have been pursuing a more "proactive approach" to address safety in the land-use and transportation planning process (Lovegrove and Sayed, 2006).

In the 1990s, a Dutch safety model commonly known as the "sustainable safety traffic system" developed several quantitative targets to reduce severe collisions through better-integrated community and transportation planning (Van Schagen and Janssen, 2000; SWOV 2006). Detecting the safer range of lane width was also one objective of several proactive safety approaches (Harwood 1990; Fitzpatrick et. al., 2001; Dumbaugh and Rae, 2009). General findings of these researchers are consistent, indicating the overdesign approach, such as wider lanes, induces higher speeds and reduces interaction between the streets users. Addressing the optimal size of travel lanes has thus emerged as one of the key design controls to correct systematic error introduced by the over-design principles of the traditional paradigm.

Livability Principles and Geometric Design Standards

Redistributing space and rescaling urban infrastructures (NJDOT 2008; Robertson 2013) while acknowledging sustainable safety limits in the context of human scale (DHV Environment and Transportation 2005, SWOV 2006, Whitelegg and Haq, 2006) has led an emerging trend in the recent evolution of sustainable city planning. Livability engineers/planners often cited the changes of lane width standard as the single most desirable practice to improve quality of life, and to adopt livable street design principles by increasing the space constrained urban area (Speck, 2014). Transportation standard-setting and research institutions responded to the call for the change to street and intersection design principles. Within less than a decade all major engineering standards and policies adopted flexible land width standards (ITE 2006, ITE 2008, AASHTO 2004 and 2010, NACTO 2013; City of Toronto, 2015 and recent on-going revision of TAC, 1999).

One of the rigorous changes to street design principles has recently become a mainstream practice due to the Complete Streets movement. With initial projects focused on reallocating street space, primarily through lane width narrowing, results started to provide an early indication and evidence of the better safety performance of narrower lanes (Parsons B. Group, 2003; Pein 2003; Longenbaker and Furth, 2008; Navazo, 2009; Miller 2009; Petritsch, 2010; and Speck, 2014). However, no direct relationship between lane width and crash frequency was presented in support of these policy changes or project outcomes. Despite updates to all major guidelines/manuals commonly used by street design practitioners, lingering concerns of the safety consequences of a narrower lane width remain a barrier to change of professional practice.

DEVELOPMENT OF SAFETY EVALUATION APPROACH

To understand the basic foundation of lane width safety principles, this paper also describes the findings of a lane width synthesis, and an analysis of other operational characteristics of a narrower lane width, relating crash frequency as a function of lane width.

Source of Database: As part of greater effort to investigate the crash occurrence mechanism for vehicle-to-vehicle crashes at signalized intersections, the collision data was collected at 190 intersections in Tokyo, Japan and 70 intersections in Toronto, Canada. Four-legged signalized intersections were randomly selected, primarily from a desktop assessment of road maps and aerials.

Similar data collection and research methodology was applied for both cities, with different land-uses, completely different street design principles, and differences in safety legislation and driving culture. To increase model efficiency, the database includes proportional representation from the various land use pattern associated collisions. Tables 1 and 2 summarize the variables and provide a comparison between the Tokyo and Toronto data.

Table 1 reveals several surprising contrast between the two cities. Tokyo managed to carry higher traffic and better travel time with lower number of travel lanes and more space for bicycles, notwithstanding similar street right-of-way. Despite higher traffic volumes and population, Tokyo’s crash rates are 34% to 80% lower compared to Toronto’s. Compact geometric design, intelligent use of public space and evidence-based safety practice is the key to Tokyo’s success.

Research Methodology and Principles: To address the topic of street safety impacted human behaviour, a primary research study was conducted in 1998~2002 to develop microscopic model for signalized intersection crashes (Karim et. al 2001). Following the original study, further research on side-impact crashes at traffic signal was carried out in Toronto in 2004~2006 (Karim, 2005). Vehicle-to-vehicle side impact crashes at signalized intersections in urban areas was the principal focus of previous research.

The key objective of both studies was the development of countermeasures designed to reduce the number of intersection crashes by applying a positive design approach. One of the principal findings of these studies was the limits of street width (pavement and right-of-way) and number of lanes that humans need to safely interact. Results indicate that a right-of-way greater than 30m and more than three lanes per approach (including turning lanes) adversely affects overall side-impact collisions, particularly right-angle collisions. These variables are used as a proxy of lane-width. The functional form used in the statistical model however, fails to identify true relationship lane width and crash rates as indicated by Hauer (2012).

Analysis Approach: The basic premise of this research is based on a logical sequence of the key findings of previous research works. Firstly, Fitzpatrick (2001) provided evidence relating speeds and lane width, concluding speeds tend to be lower for narrower lanes. And when lane widths are1 ft greater, (85th percentile) speeds are predicted to be 4.7 kmph faster. Secondly, crash severity increases exponentially with vehicle speed (Rosén and Sander, 2009; Government of South Australia, 2011), particularly for pedestrians. Thirdly, simple physics implies that higher operating speeds give drivers less time to react to unforeseen hazards and result in increased force of impact when crashes occur (Ewing and Dumbaugh, 2009).

Following this logic sequence, wider lanes will increase speed, making more time to react necessary and thus, increasing the collision risk (see detail in Figure 2). The traditional belief that “wider is safer” is highly questionable and contradictory to this logic sequence. On the contrary, narrow lanes that are physically narrower than a vehicle's width must be unsafe. Between wide and narrow lanes, there must a "safer range of lane width" where drivers feel more comfortable and less risky. Finally, following the findings of safer range of lane width by several previous researchers, it is generally agreed that safety benefits bottom out beyond a certain range of lane width, probably 3.4m for urban streets (Noland, 2002; Potts et. al. 2007; Sinclair K.M., 2011) and 3.6m for two-lane highways (Hauer, 2012).

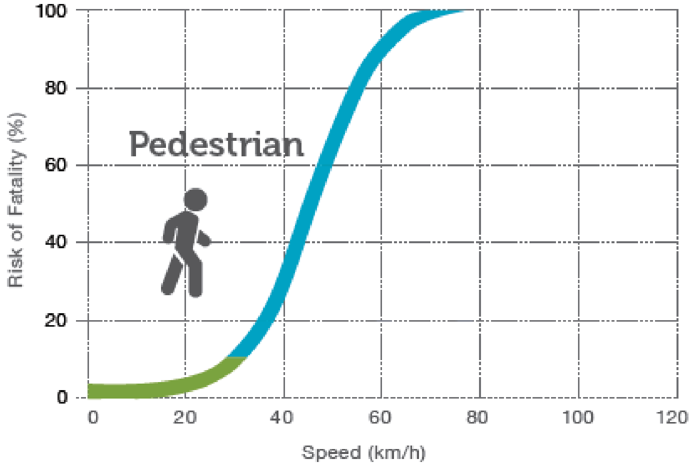
Table 1: Summary Statistics of Continuous Explanatory Variables

	Tokyo Data (1992-1995) 190 Intersections				**Toronto Data (1999-2004) 70 Intersections**			
Continuous Variables	**Mean**	**Standard Deviation**	**Minimum**	**Maximum**	**Mean**	**Standard Deviation**	**Minimum**	**Maximum**
Rear-end collisions per approach*	0.43	0.61	0	11	*	*	*	*
Left-turn collisions per approach	0.42	0.63	0	12	0.61	0.64	0	4
Right-angle collisions per approach	0.11	0.25	0	4	0.50	0.56	0	5
Right-turn collisions per approach	0.11	0.24	0	4	0.17	0.20	0	1
Side-impact collisions per approach	N/A	N/A	N/A	N/A	1.68	1.16	0	8
Daily left-turn traffic volume of the entering approach	2701	3146	10	47373	845	922	0	8160
Daily through traffic volume of the entering approach	12447	10058	10	52962	7740	4397	0	23249
Daily right-turn traffic volume of the entering approach	2784	2799	5	39140	1246	942	0	8346
Posted speed limit on entering approach (km/h)	48.13	9.26	20	60	42.12	8.20	20	60
Average speed at the time of collision (km/h)	22.03	9.42	0	54	29.48	18.17	0	80
Total number of entering approach lanes	1.83	0.83	0	5	2.36	0.95	1	5
Percentage of heavy vehicle in total traffic volumes	15.4%	5.3%	5.3%	41.2%	4.9%	1.9%	1.4%	12.3%
Percentage of bicycles in total traffic volumes	23.0%	1.8%	0%	35.0%	1.6%	2.3%	0%	5.4%
Road width of entering approach (m)	18.02	8.33	4.00	50.00	18.84	6.10	0.00	49.50

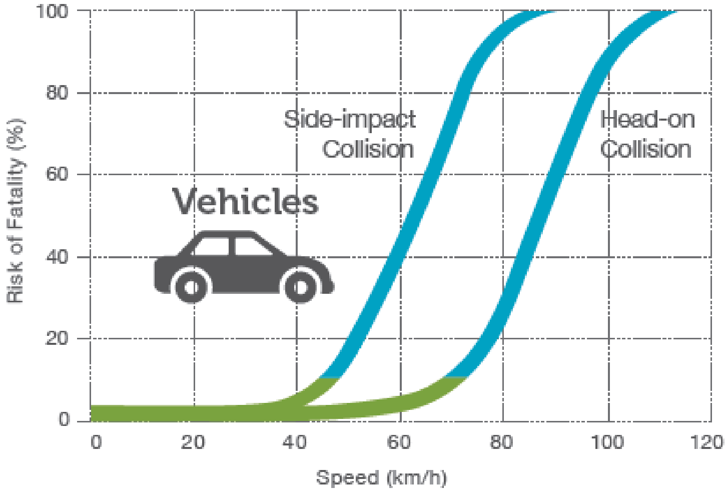
Note: *Rear-end crashes were not analyzed for Toronto research project.

Two simple variables were developed to test the research hypothesis. Average lane widths were calculated from approach widths. Collision rates were derived from both crashes per intersection per approach per year, and collision per million vehicle km, to avoid the pitfalls of each method. Based on the previous findings, this study compared average lane width with average collision rates. Similar relationships were tested against three major types of side-impact crashes using a non-linear best-fit curve. Other operational characteristics and lane width factors were then compared against the various ranges of lane width.

A debate on lane width has become the norm between engineers and planners during each complete streets project. To settle this debate, several surprising but identical evidences have been discovered for both cities, while investigating lane width and collision rates during several complete streets projects in the greater Toronto area.



Source: Government of South Australia (2011).



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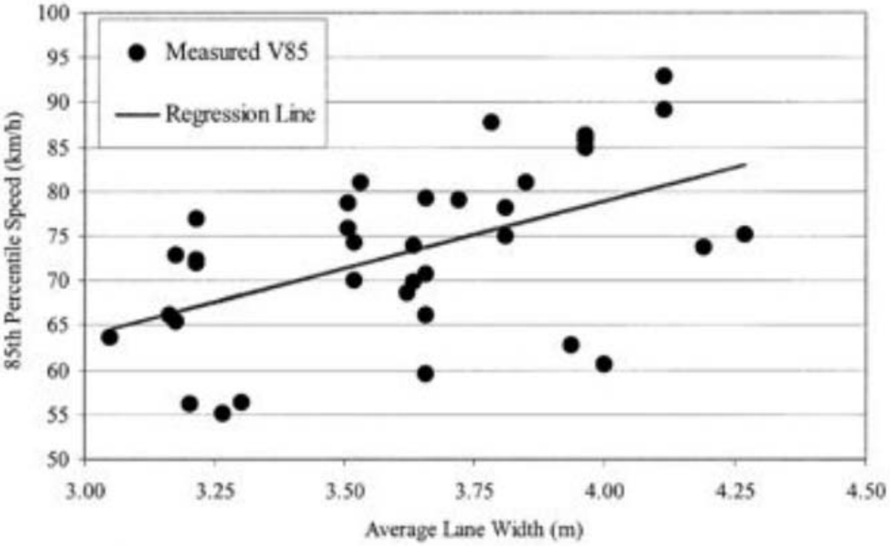

Source: Fitzpatrick et. al. (2001).

Figure 2: Collision risk of fatality, vehicle speed and lane width analysis results:

Table 2 shows the model estimation results for all types of crashes in Toronto and Tokyo including left-turn, right-angle, and right-turn collisions. The tables include the estimated coefficients and R-squared of the regression of collision models. The R-squared is the same as the square of the correlation between your dependent variable (crash rates) and independent variable (lane width). The co-efficient describes the size of the effect of independent variable (positive and negative signs indicate increase and decrease of dependent variable with respect to unit change of independent variable) are having on dependent variable and constant represent the value of dependent variable to have when all independent variables are equal to zero. Goodness-of-fit statistics indicate that the lane width variable explain the variation (between 55% and 84%) that are explained by non-linear regression models.

Table 2: Summary Statistics of Continuous Explanatory Variables

Types of Crashes	**Regression Equation**	**R^2**
All Side-Impact Crashes (Toronto)	y = 0.213x2 - 1.371x + 2.401	0.835
All Crashes (Tokyo)	$y = 0.645x^2 - 4.566x + 8.80$	0.556
Right-Angle Crashes (Toronto)	y = 0.106x2 - 0.676x + 1.222	0.602
Left-turn Crashes (Toronto)	y = 0.860x2 - 6.319x + 12.54	0.689
Right-turn Crashes (Toronto)	y = 0.926x2 - 6.779x + 12.51	0.723
Symbols	Y = Crash rates per mil entering vehicle X = Lane width (m)	

Shape of Crash Risk and Lane Width: Several surprising but identical evidences are discovered for both cities (See Figure 3). The analysis establishes a non-linear relationship between lane width and crash rates that identifies a "safety valley curve". The safety benefit increases with lane width but bottoms out around 3.1m (for Tokyo) and 3.2m (for Toronto). Consequently, lane width wider than 3.3m adversely affects overall side-impact collisions, particularly right-angle collisions. Three novel policies to enhance safety show promise from the upshots of this analysis. First, narrow lanes, particularly lane width less than 2.8m, increase the risk of side-impact crashes. Second, lateral displacement of driving maneuvers or oscillations stays within a narrow range (0.2m from bottom of safety curve). This implies that humans display a surprisingly narrow "safety comfort zone" while trying to achieve a dynamic equilibrium status within the travel lane width. Finally, wider lanes (over 3.3~3.4m) are associated with a higher speed and lower security feeling that leads to higher crash risks. These findings have a cascading system effect because lane width plays a fundamental role of distributing public space within the right-of-way. The results also clearly demonstrate why "conventional wisdom of lane width" does not hold up to scientific scrutiny.

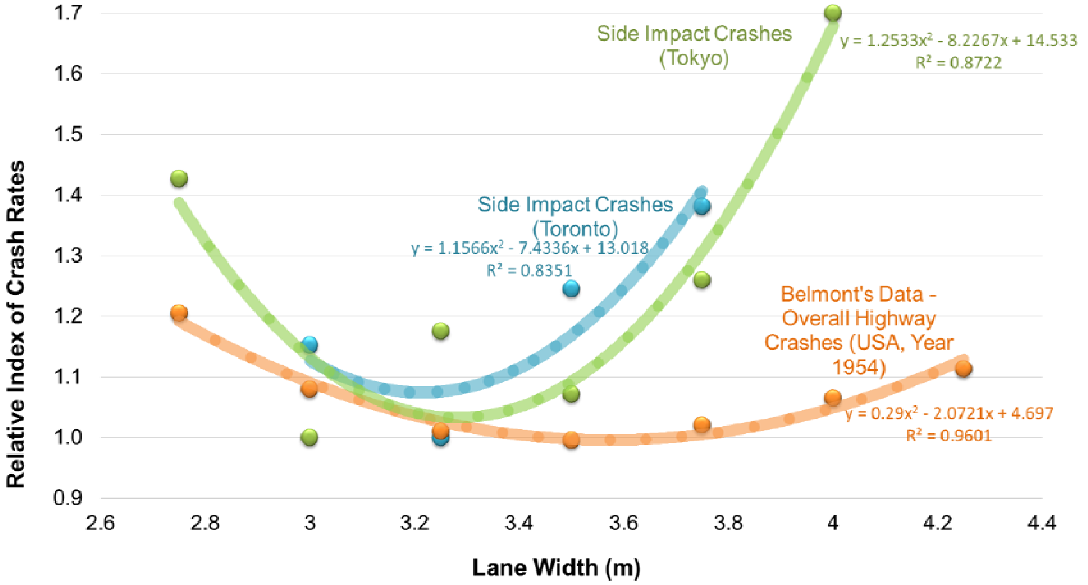

Figure 3: Relationship between lane width and crash rates

Shape of Crash Risk and Lane Width for Different Types of Crashes and Lane Uses: Types of crashes show slightly different variation for the safer range of lane width. Among the types of crashes, right-turn crashes are relatively sensitive to lane width, while safer range of lane width is relatively narrower for right-angle and left-turn crashes (Figure 4). This translates to left-turn and inner travel lanes needing to be narrower (between 2.8 and 3.1m) compared to outer curb lanes (between 3.2 and 3.6m). The sizes of curb lanes depend on the presence of large vehicles and the types of large vehicles, and the presence or absence of bicycle lanes. This result is consistent with Sando and Moses (2009) which indicates relatively higher sideswipe crash risks for transit vehicles with 3.0m lane width in absence of bicycle lanes. However, presence of bicycle lanes provides an additional buffer or safety margin, thus the curb lane with transit vehicles can be narrower (3.0~3.3m). These results indicate the lane width varies with the context of street uses. Competing interest for multiple modes can be carefully balanced if lane width is selected based on land-use context and safety of vulnerable street users.

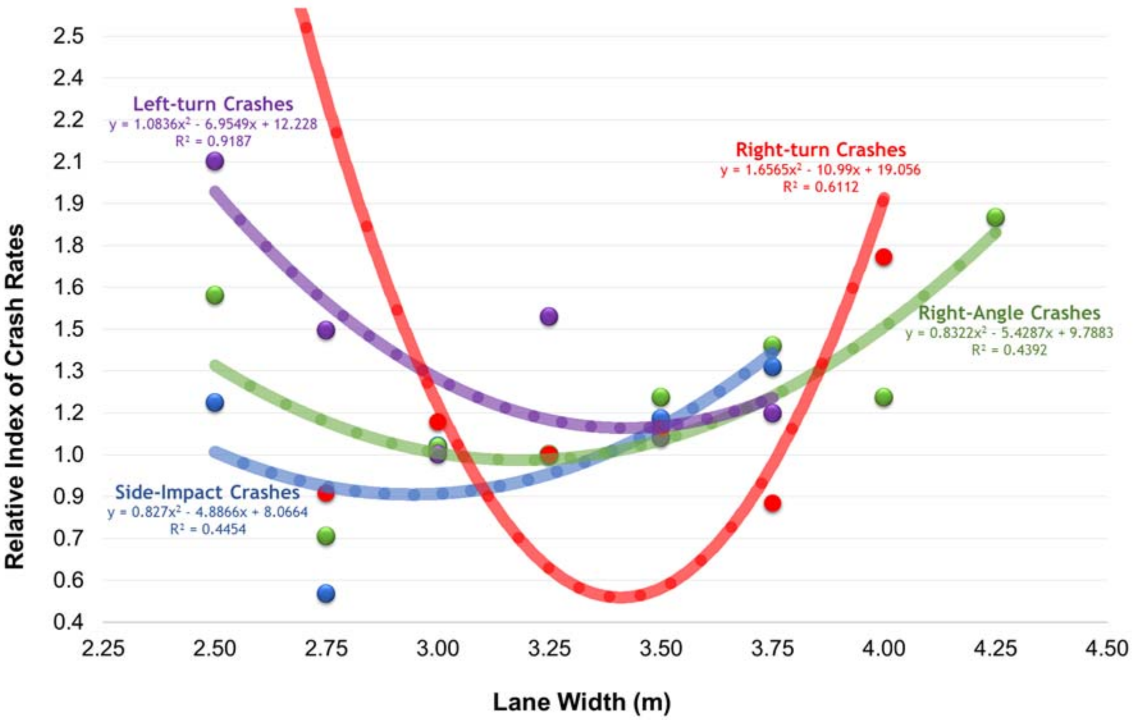

Figure 4: Relationship between lane width and crash rates for different types of collisions (Toronto) – Using lane volume only

Practice of Lane Width Selection in Tokyo and Toronto: The aforementioned safety findings were compared against actual inventory lane width in Tokyo and Toronto. Figure 5 illustrates a significant gap in professional practice by Tokyo and Toronto transportation practitioners. Despite the similarity, the database shows practitioners in the Toronto area tend to use wider lane widths, particularly in suburban areas, whereas two-thirds of travel lane width in Tokyo stays within the safer limit (less than 3.3m). Street design standards in Tokyo are developed based on real crash experiences for different ranges of lane width. Professional practices, followed by evidence and constrained space in Tokyo, restricted the wide spread practice of wider lanes. The results of these practices reflected are in safety performances. Crash rates are significantly lower in Tokyo despite relatively higher traffic volume (1.6 to 3.2 times higher) and a seven times larger population than Toronto (Table 1). Compact geometric design, such as narrower but safer range travel lanes, is the key to Tokyo’s safety success.

These findings illustrate that the practice of overdesign in Toronto leads to systematic error, and that the inevitable statistical outcome of a "wider is safer" engineering approach is the loss of precious life, specifically by vulnerable citizens.

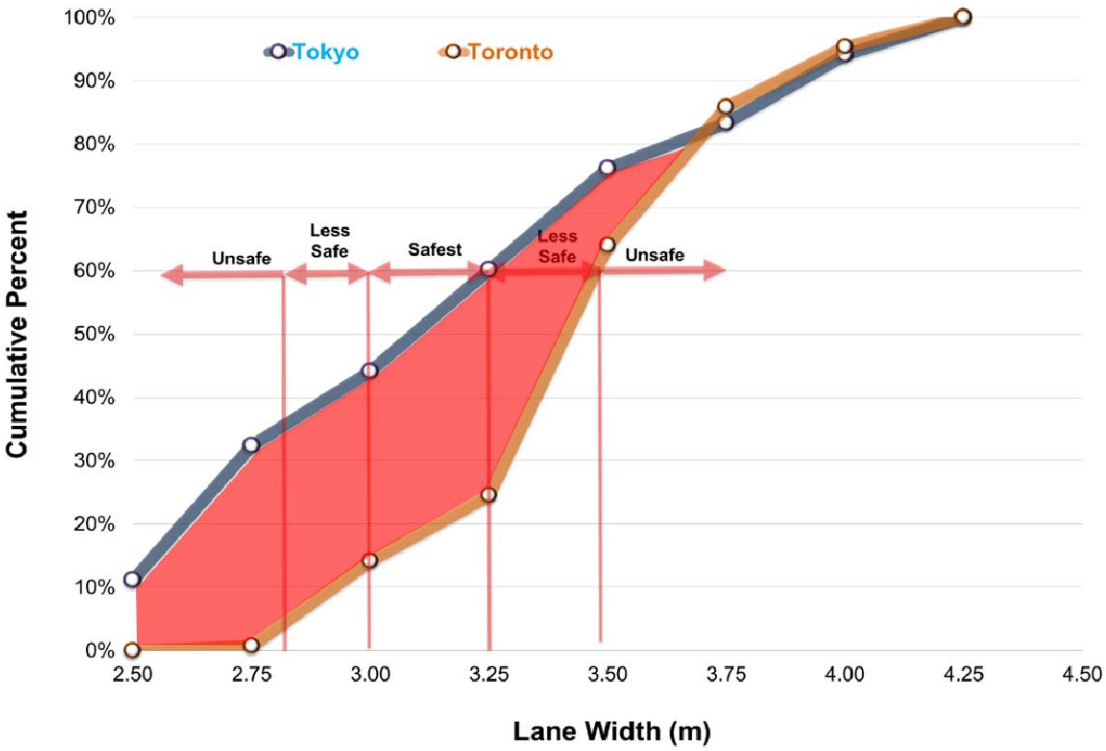

Figure 5: Distribution of lane width for Tokyo and Toronto

Influence of Narrower Lanes on Speed: Instead of collecting speed data at intersection approaches, this study utilizes the average speed at the time of collision. Table 1 summary indicates that average speed at the time of crash is 34% higher in Toronto compared to similar types of intersection crashes in Tokyo. It should be noted that speed may have been a contributing factor in 42 percent of the pedestrian collisions at the top 100 locations in Toronto (City of Toronto, 2013b). Comparing Figure 5 and average impact speed from Table 1, it is evident that the practice of lane width overdesign in Toronto results in higher average speeds. On the contrary, the practice of narrower lanes in Tokyo is associated with a lower impact speed of crashes. The causal link between speed and safety is well-established in the literature. Reducing lane width leads to lower speeds and collision frequency (Milton and Mannering, 1998; Sawalha and Sayed, 2001), the effects depending on lane widths and road types (Flides and Lee, 1993).

However, a detail review of lane width by Rosey et. al. (2009) found inconsistencies among several studies. These studies, on the contrary, confirmed the detrimental effects of a wider lane width. Studies show wider lanes increase travel speeds (Fildes et. al. 1987). And, after reviewing rigorous research on road width, lane width and speeding, several studies found the root cause is excessive operating speed (Fitzpatrick et al., 2001; Poch and Mannering, 1996; Farouki and Nixon, 1976) since higher speed vehicles need bigger gaps, and the greater the width available, the greater the vehicle speed.

The majority of drivers, particularly in suburban areas, operate above posted speed limits (Mitchell, 2012). Reducing the lane width could be an effective tool to undermining excessive speeding above the speed limit in urban areas. It should be noted that narrower lanes bring down operating speeds close to safer speed limits, while maintaining consistent speed and minimum impact on corridor travel time.

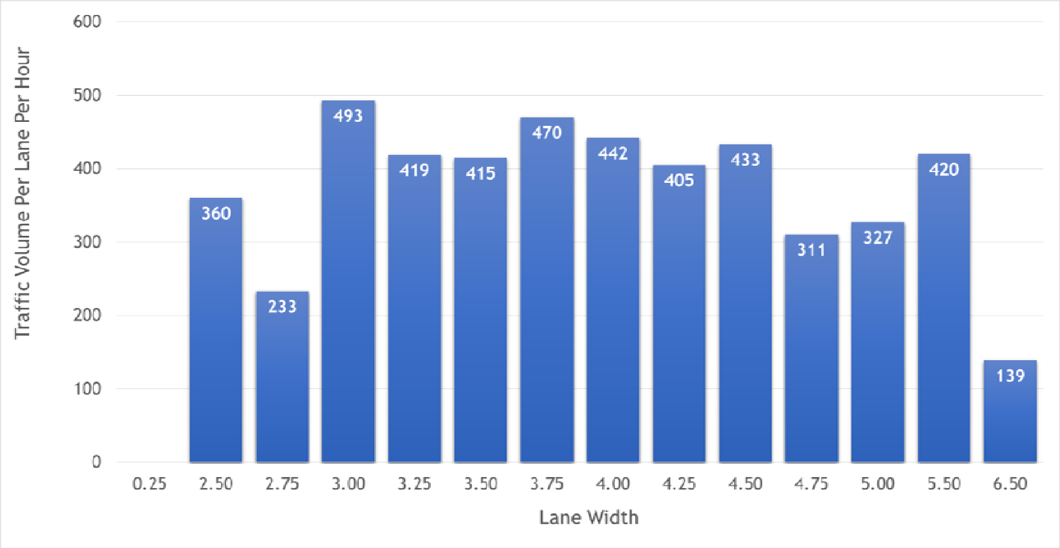

Figure 6: Distribution of traffic capacity (per lane per hour) demand and lane width (Toronto)

Impact on Traffic Capacity and Congestion: Similar to safety, narrower lanes often faces common opposition from conventional engineers believing they will reduce the “capacity” of the road. To address this issue, this study investigated both lane capacity (traffic volume per lane per hour) and total approach traffic volume with respect to the distribution of lane width. Contrary to common belief, the results clearly demonstrate that narrower travel lanes, particularly 3.0m lanes, carry the highest traffic volumes (18% higher compared to 3.5m lane) during weekdays under both scenarios (See Figures 6 and 7). Narrower lanes are generally selected for inner lanes, which face lower interactions. Wider lanes introduce unstable maneuvering and higher interactions, particularly curb lanes. Petrisch (2010) concluded that there is no measurable decrease in urban street capacity when through lane widths are narrowed from 3.7m to 3.0m. A reduction of capacity due to lane narrowing was suggested in HCM (2000), and a correction was introduced in the latest version of the manual (HCM 2010) for interrupted traffic flow at intersections. Traffic delays on urban roads are principally determined by junctions, not by midblock free flow speeds. Reducing lane width to 3.0 m in urban environments should therefore, not lead to congestion. Introducing turning and bicycle lanes to reduce lane width increases the “overall person” carrying capacity of the street. Thus, the debate on capacity due to lane width reduction does not hold up to scientific scrutiny, nor does this misperception consider increasing the “person capacity” instead of moving vehicles only.

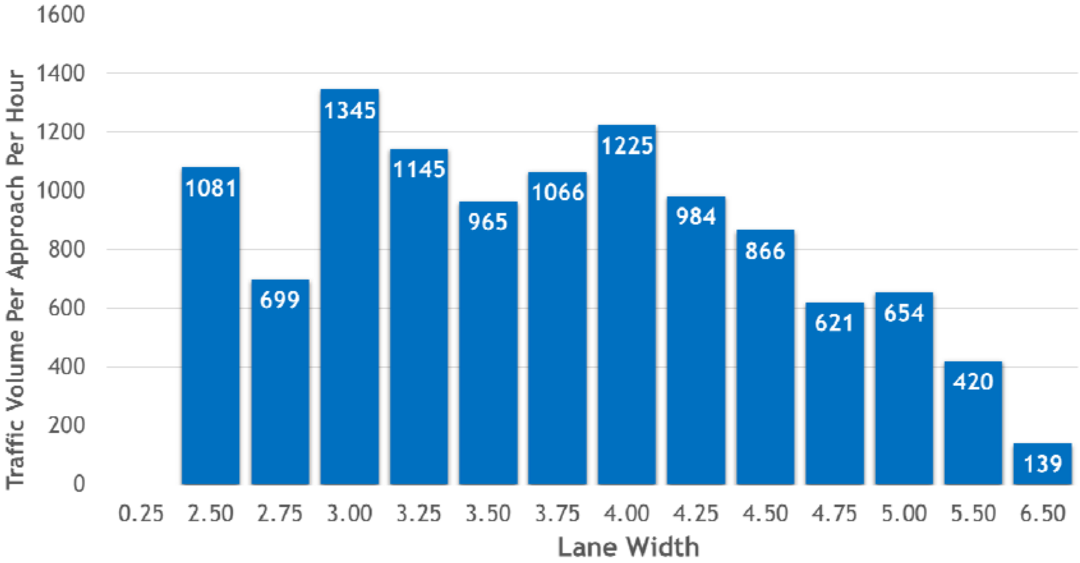

Figure 7: Distribution of approach traffic volume demand and lane width (Toronto)

Effect of Narrower Lanes on Pedestrian and Cyclists: Wider lanes heavily impact vulnerable users, particularly at intersections. Figure 8 illustrates that narrower lanes increase bicycle and pedestrian volumes, and extra vehicle space significantly deteriorates pedestrians' comfort and level-of-service. Cycling volumes increase with wider curb lanes or on collectors/local streets where vehicles share space with cyclists. It should be noted that facilities for cyclists were close to non-existence during the period of data collection (1999~2004). To improve deteriorating conditions for active transportation users, the City of Toronto (2015) recently published lane width guidelines, identifying high pedestrian activity* and moderate cyclist volumes** as an influencing factor to reduce the lane width while balancing the needs of active transportation users and equitable distribution of public space. (***High pedestrian activity:** street segments with high ratio of pedestrian crossing volumes to vehicular volumes. 1 - street segments with high ratio of pedestrian crossing volumes to vehicular volumes: greater than or equal to 2 pedestrians to 10, or 2 - high volume of pedestrian crossings: greater than or equal to 3500 pedestrians during 8-hour crossings at the nearest signalized intersections.)(****Moderate cyclist volumes:** two-way volume of 20 or greater cyclists during the peak hour along a street segment.)

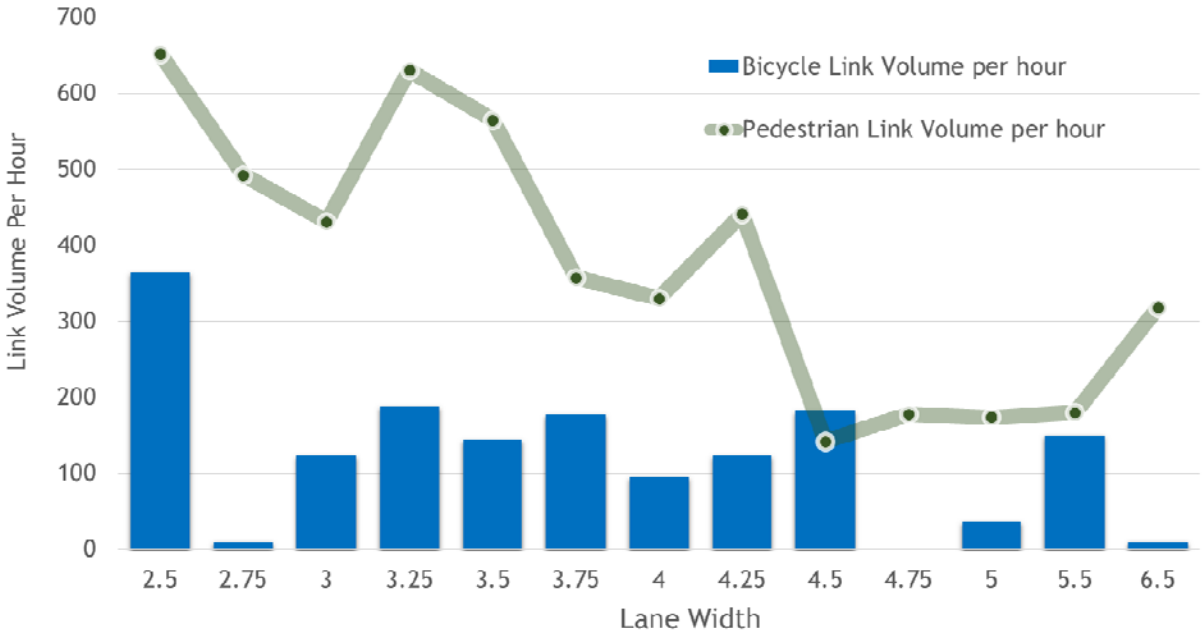

Figure 8: Distribution of link pedestrian/cycling volume and lane width (Toronto)

Large Vehicles and Narrower Lanes: Safer accommodation of large vehicles, particularly trucks, buses and emergency vehicles are sensitive issues while selecting the size of lane width. To test the assumption that large vehicles cannot use relatively narrower lanes, a percentage of large vehicles were compared against a different lane width category. Contrary to conventional belief, Figure 9 illustrates no difference in large vehicle percentages found between narrower (3.0 to 3.3m) and wider travel lanes (over 3.3m). Curb lanes are generally wider than other travel lanes and thus carry slightly higher large vehicles, but the difference is insignificant. The degree of truck proportion in total traffic, and their separation distance from bicycles influences the lane width selection. Oregon DOT (2013) concludes that the low volume trucks (less than 5%) experience no operational problems for narrower lane widths and suggests considering extra width on streets with more than 10 percent trucks, and streets with horizontal curves and tractor-trailer combination trucks. In addition, Pein (2003) reviewed the issue of side forces on bicyclists from passing heavy trucks, and provides operational rationale for increasing lane width and separation distance where speeds are very high. To stay below a tolerance limit of 1.81 kgs side load, bicyclists require a separation distance of approximately 1.5m from heavy vehicles traveling 90 kmph and 1.8m separation requirement at 96 kmph. Separation requirements are low (0.5~1.0m) for slower urban streets. City of Toronto's (2015) guidelines identify high truck volume (streets with an 800 or more 8-hour through truck volume total in both directions) as an influencing factor when lane width is selected for urban streets, particularly on arterial streets. For buses, it suggests using 3.3m for mixed traffic conditions and 3.0m where buffered bicycles lanes exist. In summary, narrower lanes do not pose any significant risks (3.0 to 3.3m) for streets with a low volume of large vehicles.

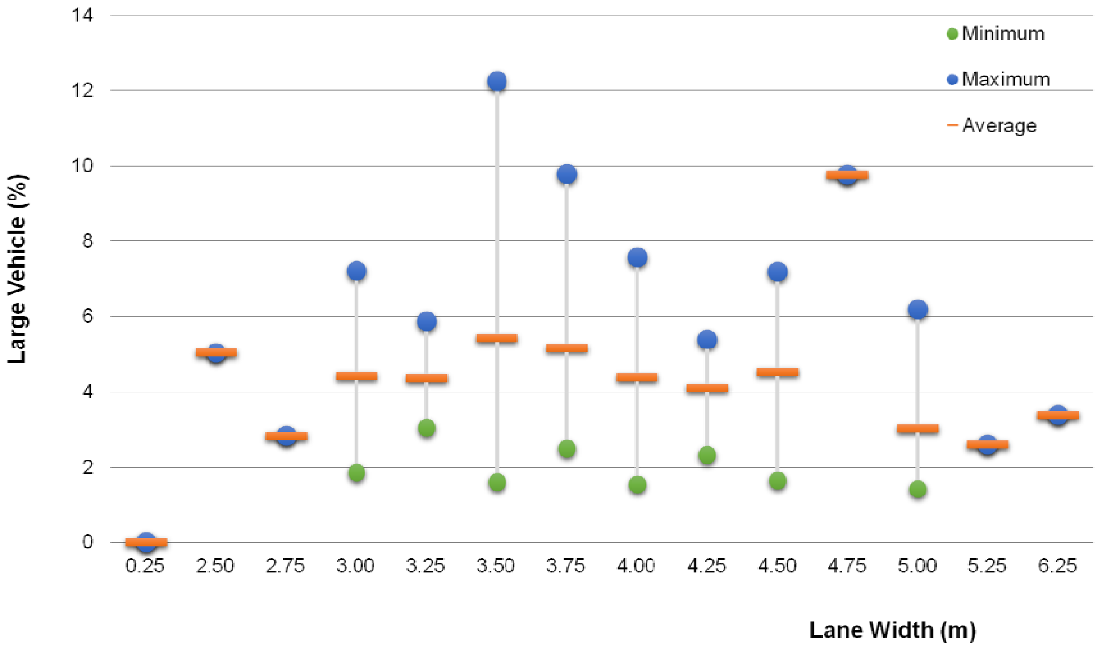

Figure 9: Large vehicle usage as per lane width (Toronto)

Emergency Vehicle Response Time and Lane Narrowing: Discussion of the impact of narrower lanes on emergency vehicles is often cited without context as what increases travel time (Dan Burden, and Paul Zykofsky, 2000). While evident in Figure 9, no difference is observed for the preference by large vehicles among various sizes of lane width. Emergency vehicles require minimum 6.0m clearance and shorter spacing for traffic signal access, particularly for streets with a median. Travel lanes should not be too narrow (less than 2.8~3.0m) for vehicles pulling out from emergency vehicles' paths, and long uninterrupted medians should be avoided. Multiple lanes leave sufficient space for drivers to pull out of the way of emergency vehicles. Contrary to common belief, that wide and open streets provide faster travel time for emergency vehicles, researchers conclude that roadway connectivity significantly affects the travel distances required to reach destinations (Ewing and Cervero, 2010; Handy et. al. 2010). Connectivity is generally very low on wider and open arterial streets, often clogged during peak hours and a source of danger to pedestrians and bicyclists. Connected streets tend to increase transportation system resilience. Increasing route options by allowing emergency vehicles more direct access, and reducing the risk that an area will become inaccessible if a particular part of the roadway is blocked by a collision or fallen tree. A more connected street system allows a fire station to serve about three times as much area as an area with unconnected streets. It also increases the efficiency and safety of services such as garbage collection and street sweeping (crashes and insurance costs tend to increase if such utility vehicles are required to frequently back up), and tends to reduce water quality problems that result from stagnant water in dead-end pipes at the end of cul-de-sacs (Handy, Paterson and Butler, 2004). Therefore, the focus should be on the context-sensitive travel lane width selection techniques that meet the needs of all users to improve safety and livability.

Notes on Lateral Displacement: In Australia, the maximum allowable width of a vehicle body is 2.5m unless it has been granted an over dimensional permit. This width does not include mirrors, so a typical bus is 2.5m wide plus side mirrors. A typical car has a body width of about 1.9m plus mirrors (Design Vehicle dimensions from Austroads, 2006b). Schramm and Rakotonirainy (2009) reviewed an Australian study which considered the theoretical operation of heavy vehicles (trucks) within a traffic lane. "Models of estimated lane width requirements for heavy vehicles were developed, based on the mean measured lateral displacement and the maximum Australian legal vehicle width (2.5m). The results indicated that a majority of heavy vehicle configurations had a lane width requirement of less than 3.2m when travelling at 90kph, and 3.1m when travelling at 60kph. Prime-movers and semi-trailers were shown to have the smallest lane width requirements, estimated at2.8m when travelling at 60kph. This research demonstrated that greater lane widths were required when travel speed increased in highway environment, although there was no measure of statistical importance of this finding.

Discussion on the Summary of Findings

The findings of this study suggest that the intuitive arguments made in the introduction hold up under quantitative analysis. The positive design approach, such as narrower lane width, promotes eye contact between all street users. Narrower lanes provide a message to large vehicle driver to be careful in urban environment. On contrary to common belief, narrower lanes also carry highest amount vehicles while maintaining consistent speed for all vehicles including emergency services. Both narrow (less than 2.8m) and wider (over 3.2~3.4m) designs have proven to increase crash risks with equal magnitude. Among the types of crashes, right-turn crashes are relatively sensitive to lane width, while safer range of lane width is relatively narrower for right-angle and left-turn crashes. The findings acknowledge that human behavior is impacted by its street environment. In conventional traffic engineering expectations the findings may seem anomalous, but the conclusions are consistent with the general safety hypothesis of an interaction between driver behavior and geometric standards.

In the natural world of street behavior, safer range of lane width can be visualized easily during certain street or weather conditions. Figure 10 depicts a visual display of a “safer zone” created by natural driving habits. Snow or construction debris displaced by drivers shows that drivers stay within a “comfortable and safer zone” despite wider space given to their vehicles. Examples on the left illustrates how unused space can be used for bicycle lanes, on the street that leads to busy high school destinations. Whereas unnecessary wider space on the right creates illegal parking problems instead of safer parking in the lay-bys. Despite these illustrations, both streets were recently reconstructed without narrowing lane width creating unsafe conditions for drivers.

The findings demonstrate that if lane widths in urban areas were reduced to less than the current guidelines of 3.5m (TAC 1999), the result could be a safer environment for all street users. Given the empirical evidence that favours ‘narrower is safer’, the ‘wider is safer’ approach based on intuition should be discarded once and for all. Narrower lane width, combined with other livable streets elements in urban areas, result in less aggressive driving and the ability to slow or stop a vehicle over shorter distances to avoid a collision.

Figure 10: Drivers display safer range of lane width under natural conditions

The study's findings have profound implications on safety and more equitable distribution of street space among transportation mode users. Context-based lane width is the key outcome of this study (Figure 11). Lane width selection is influenced by land-use context, types of vehicles or users sharing the street, types of travel lanes or waiting/queuing lanes for vehicles, and presence of dedicated or shared bicycle facilities. Using these guidelines, wider pavement space can be reallocated and avoid expansive widening, saving public funding and addressing systematic errors introduced by the overdesign of lane widths. Street designers can utilize the identified "unused space" to provide an enhanced public realm, including cycling facilities and wider sidewalks, or to save money on the asphalt not used by motorists.

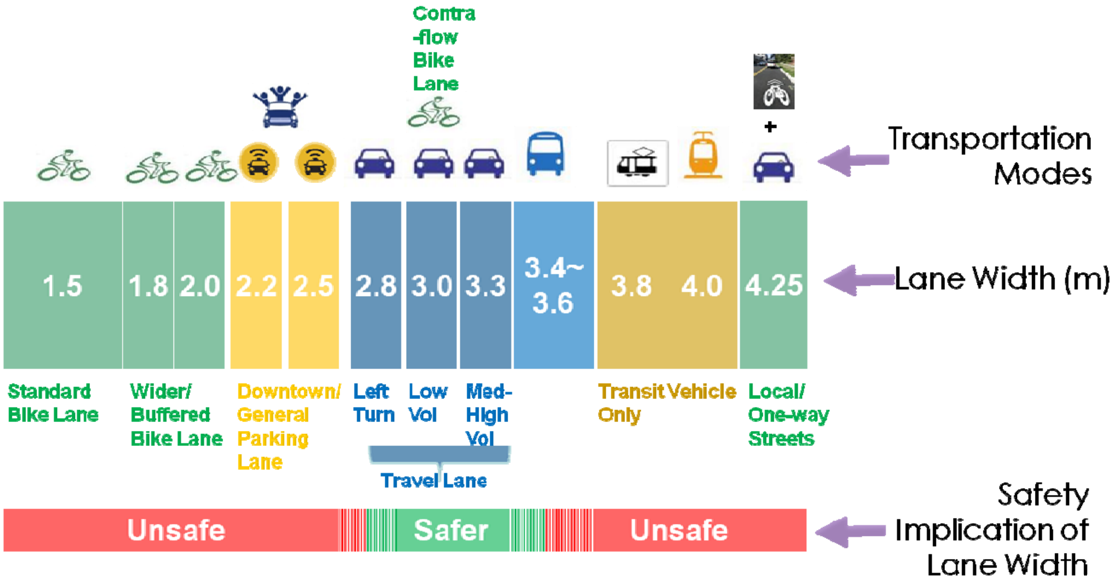

Figure 11: Context-based lane width selection for different users and land-use environments

CONCLUSIONS

The study results align with original research indicating compact sizes reduce speed near conflict points, reduce exposure for vulnerable users, and increase visibility and interactions between all users. Several emerging design approaches, such as "Streets for People" (Government of South Australia, 2012), present key principles to shape pedestrian and cycling-friendly streets by mixing in a "Link and Place" concept. Similar concepts are emerging, popularly known as "30 by 30", restrict residential street size to 30 metres and the speed limit to 30 km/h. "Vision Zero" a safety model pioneered in Sweden in 1997 (Whitelegg and Haq, 2006) is reducing traffic fatality to near zero. In short, one of the keys to rescaling urban streets with narrower lanes is integrating the planning, design and management of urban spaces to solicit multi-disciplinary expertise, and capture the different factors that influence human behaviour.

DISCLAIMER

The views expressed in this article are those of the author and do not necessarily reflect the views of the City of Toronto or the City's Planning Department.

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