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Urban road space allocation incorporating the safety and construction cost impacts of lane and footpath widths

Tiantian Chen[a], **N.N. Sze**[b], **Sikai Chen**[c], **Samuel Labi**[d]

[a] Dept. of Civil & Environmental Eng., The Hong Kong Polytechnic University, Hong Kong, Email: tt-nicole.chen@connect.polyu.hk

[b] Dept. of Civil & Environmental Eng., The Hong Kong Polytechnic University, Hong Kong, Tel: +852 2766-6062; Email: tony.nn.sze@polyu.edu.hk, **Corresponding Author.**

[c] Lyles School of Civil Eng., Purdue University, W. Lafayette, IN, USA; and Robotics Institute, School of Computer Science, Carnegie Mellon University, Pittsburgh, PA, USA. Email: chen1670@purdue.edu; sikaichen@cmu.edu

[d] Lyles School of Civil Eng., Purdue University, W. Lafayette, IN, USA Email: labi@purdue.edu

Highlights

- This study developed an optimal width allocation policy for two-lane road vehicle lanes and footpaths in a constrained urban space.
- When user (safety) and agency (construction) costs are considered equally important, the optimal lane width is 5.4 m and, any remaining road space is allocated to the footpaths.
- Through backcalculation using the developed methodology, it is observed that the road space allocation ratio used by the Hong Kong road agency suggests that the agency places a higher weight to user (safety) cost compared to agency (construction) cost.
- For a given, limited urban road space, footpath widths could be allocated to reflect commensurately, the importance the agency places on pedestrian safety specifically and urban walkability in general.

Abstract

Walkability continues to attract great attention from urban planners, designers, and engineers as they recognize not only the merits of pedestrian facilities in terms of the health benefits but also their demerits in terms of accident risk to pedestrians. Wide footpaths improve the pedestrian environment and experience, and thereby motivate travelers to walk as much as possible. However, if footpaths are too wide, they may leave a smaller space for the roadway. On the other hand, wide road lanes may lead to higher road vehicle safety but are costly to construct and maintain and also may leave little space for the footpath. Evidently, for a fixed urban space, what is needed is an optimal balance between the vehicle lane and pedestrian path. This problem is encountered routinely in dense cities including Hong Kong where land availability is severely limited. To address the issue, this paper first establishes safety performance functions (SPFs) for the pedestrian space and the road space, using the random-parameter negative binomial regression. The results indicate the extent to which road lane and footpath width changes are associated with changes in in-vehicle occupant and pedestrian casualties. Then the paper uses the SPFs to develop a methodology for optimizing the width allocations to the road lanes and footpaths, duly considering the user (safety) costs and agency (construction) costs associated with each candidate allocation of the widths. Finally, the paper analyzes the sensitivity of the optimal solution to the relative weights of user cost and agency cost. The findings can help incorporate design-safety relationships, and the stakeholders (agency and users) perspectives in urban road and footpath design.

Keywords: Road safety, footpath, width allocation, safety cost, life cycle cost.

1. INTRODUCTION

Most large cities worldwide have high levels of population density, building development, and employment concentration. As populations continue to grow, the demand for human activities, including transportation, increases the need for efficient use of limited road spaces. This, in turn, leads to or exacerbates traffic congestion and noise, air pollution and vehicle emissions, and vehicle and pedestrian accidents. The high toll of vehicle and pedestrian traffic death and injury has profound adverse impacts on the public health, economy, and the social well-being of city residents (WHO, 2018a). In cities, therefore, it is imperative to ensure cost-effective and efficient utilization of the scarce land, to promote sustainable development of the city infrastructure. In the context of vehicle and pedestrian transport in cities, there often exists a competition for space. As a prerequisite to finding a good balance between road and pedestrian facilities in a limited urban space, it is essential to revisit the influential factors of vehicular and pedestrian crashes. For this reason, we first discuss some relevant issues associated with urban pedestrian traffic, vehicular traffic, and their sharing of the road space, and then present the problem statements and study objectives.

1.1 Pedestrian Infrastructure and Crashes

The pedestrian mode of transport has a dichotomous effect on the wellbeing of pedestrians. On one hand, this mode is consistent with urban walkability which has been determined to have beneficial effects in terms of personal health (Asadi-Shekari et al., 2015; Stevens and Salmon et al., 2014; Zegeer and Bushell, 2012). For this reason, walkability is increasingly being promoted through city planning initiatives including landscape policy, context-sensitive design of footpaths, land use, access to buildings and businesses, traffic management, pedestrian facility design (Martin, 2006; Sze and Wong, 2007; Gitelman et al., 2012; Sze and Christensen, 2017) and vehicle traffic enforcement (Chen et al., 2020).

On the other hand, the pedestrian mode of transport uses dedicated infrastructure in the neighborhood of the vehicle carriageway or at some locations, shares the roadway space with road vehicles. For this reason, pedestrian traffic is susceptible to traffic conflicts with vehicles, and this leads to a situation where the pedestrian modes experiences a rather disproportionate number of crashes and related injuries and fatalities compared with other transport modes (WHO, 2018b). It has been established that pedestrians are more vulnerable to more severe-injury and fatal crashes compared to road vehicle occupants, as the data shows that they experience higher rates of these adversities (Sze et al., 2019a; Zhai et al., 2019; Sze and Wong, 2007). In Hong Kong, for example, most of the 19,500 road casualties and 130 road deaths annually, are suffered by pedestrians (Transport Department, 2018). In the United States, annually, 5,000 pedestrians are killed in traffic crashes (representing 12% of all traffic deaths), and 70,000 pedestrians are injured (Ronkin and Allred, 2010) even though pedestrian traffic accounts for very little of the overall person-miles of travel.

To protect the benefits associated with pedestrian transportation and to reduce the adversities associated with this mode as discussed above, urban transport engineers continue to undertake a variety of initiatives. These include the adoption of urban landscape policies, pedestrian-dedicated designs that limit pedestrian exposure to vehicles, and consequently, reduce pedestrian crash frequency and severity. Specific examples are footpaths to prevent pedestrian use of the vehicle carriageway, and adequate widths of pedestrian rights-of-way to serve as a buffer between pedestrian and vehicular traffic. In addition, crosswalks, islands, curbs, fences, and bollards are typically used to protect pedestrians that walk along, cross, or wait to cross the roadway. These designs therefore generally help reduce potential pedestrian-vehicle conflicts and injury/fatality risks (Hu and Cicchino, 2018; McMahon, 2002).

1.2 Road Vehicle Infrastructure and Crashes

Several studies have discussed the relationships between specific aspects of the road infrastructure and safety. A particular aspect of this relationship that is relevant to the present study, is the link between road lane width and vehicular crash frequency and severity (Chen et al., 2017a; Wu et al., 2015; Pei et al., 2012; Gross and Jovanis, 2007). Park et al. (2012) and Chen et al. (2017b) determined the extent to which the vehicle lane width, within a certain standard range, correlates negatively with the frequency of different vehicle crash patterns or severity levels. An increase in the lane width by 1 ft could result in a 2% decrease in vehicle crash frequency (Abdel-Rahim and Sonnen, 2012). Therefore, wider lanes generally promote vehicle safety.

1.3 Sharing the Road Space

The cross-sectional elements of a roadway consist mainly of the carriageway space and an “extra” space on the left and right side of the carriageway. The carriageway (also referred to as the travel way or vehicle lanes) is that portion of the roadway used by vehicles. The extra space on the left and right side have functions that depend on the road location – rural vs. urban. In rural areas, the extra space is occupied by a shoulder that serves as a refuge for collision avoidance or storage for stalled vehicles. In urban areas, the situation is generally different, as the landscapes are characterized by relatively small space between adjacent buildings that must be shared by the road (for vehicular traffic) and the footpaths (for pedestrians). In very few cases, there is space for other features such as decorative vegetation, and barriers and fences. At most urban areas, therefore, the extra space refers to a footpath width for pedestrian use.

For a given overall roadway width constraint, a wider carriageway is beneficial for road vehicle safety; however, this would result in smaller space for footpaths and therefore, inimical for pedestrian safety. Similarly, a narrow carriageway is harmful for road vehicle safety but would result in larger space for footpaths and, therefore, would promote pedestrian safety. Clearly, for a given total roadway width, the road agency needs to determine the best distribution of the space between the carriageway and the extra space (shoulder or footpath). Such determination can be informed by analysis of the safety performance trade-offs between the carriageway and footpath spaces. The analysis should recognize the need to maximize the user benefits (in-vehicle and pedestrian safety) without the agency cost of constructing and maintaining the carriageway and the extra space. For rural roads, several past studies have discussed the safety effect of the shoulder width (NHTSA, 2019; Rezapour et al., 2019; Gross and Donnell, 2011; Chen, 2019; Gross et al., 2009; Gross and Jovanis, 2007; Zegeer and Perkins, 1980) and others have investigated optimal width allocation policy between the carriageway and the shoulder for rural roads (Labi et al., 2017). For urban areas, there is limited or no guidance on the issue, and the current paper seeks to address this gap in the literature.

1.4 Problem Statement and Study Objectives

From the previous discussion on pedestrian traffic and vehicular traffic in urban areas, and their impacts and associated space needs in a land-constrained urban environment, it is clear that it can be useful to establish an effective width allocation policy for the vehicle lane and the pedestrian footpath. As is the case with any evaluation problem, it is sought to do this in a manner that optimizes the costs and safety performance associated with the road and the footpath.

In addressing this gap in the literature, the objective of this paper is to develop an optimal roadway width allocation policy that is based on two stakeholder considerations: the agency (construction cost) and the users (safety benefits to vehicle occupants and pedestrians). In this manner, the footpath widths can be designed to improve urban walking environments, thereby promoting walkability and enhancing the overall social well-being of the community without disproportionately compromising the perspectives of other stakeholders, that is, the agency (via the facility construction cost) and the users (safety of on-road vehicle occupants). From a broader perspective, the paper is intended to support the engineering decisions of urban planners and managers regarding the provision and dimensions of pedestrian infrastructure.

The remainder of this paper is organized as follows. Section 2 describes the analysis method including the safety performance function, accident cost estimation, and optimization. Section 3 describes the data used in the study. Section 4 presents the results and policy implications. Finally, a summary of findings and directions for future research are discussed in Section 5.

2. METHODOLOGY

The methodology in this paper was designed to yield an optimal allocation policy for the widths of vehicle lane and footpath of two-way two-lane urban roads given a fixed total road width (TRW). The objective of the optimization problem is to minimize the total life-cycle cost which consists of the agency cost (i.e., construction and maintenance costs) and safety cost (i.e., accident cost). Relative weights were assigned to the agency's perspective (construction cost) and the user perspectives (vehicular and pedestrian crash costs). Then the overall cost was calculated as the weighted sum of these costs. The decision variables are the total vehicle lane width (TLW) and the total footpath width (TFW). Details of the user and agency cost estimations and optimization formulation are provided in the following sub-sections.

2.1 Safety cost

For the urban space allocation problem in this paper, the key consideration is a model that quantifies the effects of lane and footpath widths on safety. In this paper, we estimate the safety performance associated with each pair of lane and footpath widths. The safety performance is measured in terms of the number of casualty victims of each type (pedestrian versus in-vehicle occupant) and the highest level of injury severity level (fatal or severe injury versus slight injury). Fatal crashes are relatively rare; therefore, in this paper, fatal crashes and severe-injury crashes are combined as a single class: fatal or severe-injury crashes (FSI). In each model, we estimate safety as a function of traffic volume and geometric design characteristics. The independent variables considered are annual average daily traffic (AADT), total lane width, total footpath width, horizontal curve density, difference in footpath width and road segment length. In past research, these variables have been found to significantly contribute to urban road crashes in Hong Kong (Zeng et al., 2017; Pei et al., 2016; Pei et al., 2012). To account for the overdispersion of casualty count and unobserved heterogeneity, we use a random-parameter negative binomial regression approach (Lord and Mannering, 2010; Anastasopoulos and Mannering, 2009). The results of the parameter estimation of the proposed safety performance functions served as inputs to the lane-footpath width optimization problem that is discussed subsequently.

A random-parameter negative binomial model was adopted to account for the unobserved heterogeneity. The probability of road segment ***i***, (***i*** =1, 2, 3..., 180) having y_{ijk} casualty crashes during a given analysis period, is:

$$P\left(y_{ijk}\right) = \frac{\mathrm{EXP}(-\mu_{ijk} \cdot \varepsilon_i)(\mu_{ijk} \cdot \varepsilon_i)^{y_{ijk}}}{y_{ijk}!} \tag{1}$$

Where: $\boldsymbol{\mu_{ijk}}$ refers to the expected number of casualties on road segment ***i*** that are of injury severity level ***j*** (*j*=1 is FSI, *j*=2 is slight injury), and casualty victim type ***k*** (*k*=1 for pedestrian casualty, *k*=2 for in-vehicle occupant casualty), as follows:

$$\mu_{ijk} = \mathrm{EXP}(\beta_i X_{ijk} + \varepsilon_i) \tag{2}$$

$$\ln(\mu_{ijk}) = \beta_0 + \beta_i \boldsymbol{X}_{ijk} \tag{3}$$

$$\beta_i = \beta + \varphi_i \tag{4}$$

$\mathbf{X}_{ijk}$ is the vector of explanatory variables (including *AADT*, *TLW*, *TFW*, *horizontal curve density (HCD)*, *difference in footpath width (DFW)* and *road segment length*); $\mathrm{EXP}(\varepsilon_i)$ is a gamma-distributed error term with mean 1 and variance α; $\boldsymbol{\beta_i}$ is the estimable random parameter with a mean vector of $\boldsymbol{\beta}$; $\boldsymbol{\varphi_i}$ refers to a normally- and independently-distributed random error term with mean 0 and variance σ^2; and $\boldsymbol{\beta_0}$ is the intercept.

In this study, the safety cost refers to the human loss associated with a road crash. It includes the medical cost, loss of productivity, human cost (i.e., loss of quality of life), property damage, and administrative cost (for example, police, insurance, and legal costs) (Sze et al., 2019b). Safety cost is often estimated in terms of the Value of Statistical Life (VSL) (Viscusi and Aldy, 2003) using the willingness-to-pay approach (Niroomand and Jenkins, 2017; Yang et al., 2016). In 2016, VSL of a road traffic fatality in the United States was estimated at 9.6 million US$, and that of severe injury and slight injury was 1 million USD and 0.29 million US$, respectively (U.S. Department of Transportation, 2016). In the case study of this paper (presented in a subsequent section), the VSL for Hong Kong was estimated based on the per capita GDP of Hong Kong and that of the United States, and the Consumer Price Index of Hong Kong in 2019 (Hong Kong Census and Statistics Department, 2019; The World Bank, 2017).

2.2 Agency cost

The total agency cost consists of road construction costs and maintenance costs. This is a function of the type of paving materials used for the carriageway and the footpath. Information on unit construction and maintenance costs of vehicle lanes and footpaths were obtained from the databases of Hong Kong Works Bureau (Hong Kong Highways Department, 2017; Hong Kong Legislative Council, 2000). The agency cost estimates are adjusted for inflation by converting to constant dollars as of Year 2019, using the Construction Cost Index in 2019 (Hong Kong Civil Engineering and Development Department, 2019). Based on information from the literature, the service lives of the footpath and vehicle lane were each assumed to be 20 years (Legislative Council, 2014; Ford et al, 2012; Markow, 2007). The life cycle cost of construction and maintenance for each paving material type is calculated over a 20-year analysis period. The selected length of the analysis period is consistent with established guidelines for pavement assets (Walls and Smith, 1998).

2.3 Optimization Framework

In a given two-lane urban road space, the allocation of vehicle lane width and footpath width that minimizes the total life-cycle cost is estimated based on the costs and benefits associated with each of the extremely large number of candidate pairs of road space allocated to these two roadway elements: the vehicle lane or carriageway width (TLW) and the footpath width (TFW). The objective function is a strictly convex function of decision variables TLW and TFW, and the optimization problem is formulated as follows:

Decision variables: *TLW*, *TFW*

Objective function:

$$\text{Minimize } C\ (TLW, TFW)$$

$$= TLW \cdot Length \cdot CC_{\mathrm{l}} + TFW \cdot Length \cdot CC_{\mathrm{f}}$$

$$+ \frac{(1+\omega)^{n}-1}{\omega\ (1+\omega)^{n}} \cdot (TLW \cdot Length \cdot MC_{\mathrm{l}} + TFW \cdot Length \cdot MC_{\mathrm{f}})$$

$$+ \mathrm{W_R} \cdot [\frac{(1+\omega)^{n}-1}{\omega\ (1+\omega)^{n}} \cdot \sum_{1}^{jk} \mathrm{C_j} \cdot \mu_{\mathrm{ijk}}\, (TLW,\ TFW)\ ]$$

Subject to:

$$\begin{cases} TLW + TFW = TRW \\ TLW \geq 5.4 \\ TFW \geq 1 \end{cases}$$

Where: $\boldsymbol{C}$ = the total life-cycle cost in HK\$; $\boldsymbol{CC_l}$ and $\boldsymbol{MC_l}$ = unit construction cost and unit annual maintenance cost, respectively, for the vehicle lane, in HK\$/m^2; $\boldsymbol{CC_f}$ and $\boldsymbol{MC_f}$ = the unit construction cost and unit annual maintenance cost for the footpath, in HK\$/m^2 (see **Table 2**); $\boldsymbol{C_j}$ = the unit safety cost for injury severity level $\boldsymbol{j}$ ($\boldsymbol{j}$ = {FSI, slight injury}, see **Table 1**); $\boldsymbol{\mu_{ijk}}$ = the expected number of casualties at road segment $\boldsymbol{i}$ for injury severity level $\boldsymbol{j}$ and casualty victim type $\boldsymbol{k}$ (from the casualty prediction models developed in this paper); $\boldsymbol{W_R}$ = weight ratio of the safety cost dollar to the agency cost dollar; **Length** = road segment length in meters; $\boldsymbol{n}$ = analysis period; $\boldsymbol{\omega}$ = discount rate;

$[(1+\omega)^n - 1]/[\omega\,(1+\omega)^n]$ refers to the uniform series present-worth factor that is used to calculate the cumulated present value (that is, the life-cycle cost) for an uniform series of payments (including the annual maintenance cost and safety cost).

The above objective function is nonlinear in nature and, the constraints are the total road width (equal to the sum of widths of the two vehicle lanes and the two footpaths), the minimum ***TLW***, the minimum ***TFW***; and the ***TRW*** range. For each design alternative (candidate pair), the overall cost was calculated in terms of the accumulated (net) present value over the life cycle.

3. CASE STUDY AND DATA

It is essential to consider the influential factors of vehicular and pedestrian crashes in a city as a prelude to allocating its limited urban road space to vehicles and pedestrians. This case study uses data from Hong Kong to carry out the urban road space allocation. With its large population and constrained land space, Hong Kong needs to utilize efficiently its scarce land. It has been estimated that Hong Kong's road and transport facilities occupy 4.1% of the city's overall developed area (277 km^2) (Hong Kong Planning Department, 2019). As of 2019, the total road length was 2,107 kilometers. In the past decade, the number of private cars in Hong Kong increased dramatically, by 48% (Hong Kong Highway Department, 2020). This, in part, explains the continuing exacerbation of traffic congestion in the city, with the attendant problems of vehicle and pedestrian accidents and vehicle emissions. Therefore, it is estimated that a total of 15,935 crashes in 2018 (including 107 fatal crashes, 1,682 serious crashes, and 14,146 slight crashes) roughly cost the Hong Kong society over 18 billion Hong Kong dollars using unit crash costs from a similar jurisdiction (Ministry of Transport, 2017).

Information on the construction and maintenance unit costs of road lanes and footpaths were obtained from the databases of the Hong Kong Works Bureau (Hong Kong Highways Department, 2017; Hong Kong Legislative Council, 2000). The agency cost estimates were adjusted for inflation by converting to constant dollars as of Year 2019, using the Construction Cost Index in 2019 (Hong Kong Civil Engineering and Development Department, 2019).

The methodology, which is described in the previous section of this paper, considers the user (safety) benefits and agency (construction and maintenance) cost impacts associated with candidate allocations of the lane and footpath widths. For the case study, crash data spanning a five-year period (2011–2015) were collected from the Transport Information System (TIS) of the Hong Kong Transport Department. The TIS database consists of three profiles: the accident circumstances (e.g., the crash time, location, type, and severity, and the road type and speed limit); vehicle attributes (e.g., the vehicle type and age), and casualty characteristics (e.g., the injury severity level, and the casualty victim age, and his/her location at time of the casualty, that is, in-vehicle vs. pedestrian). The in-vehicle occupant may refer to the driver or a passenger. In Hong Kong, the injury severity level of road casualties (fatality, severe injury, or slight injury) is determined from police records as part of the crash scene investigation and from trauma records within 30 days of the crash. In this paper, fatal crashes and severe-injury crashes were combined as a single class: fatal or severe-injury crashes (FSI).

Data on the road geometry parameters and traffic flow were collected from Hong Kong Transport Department’s Annual Traffic Census (ATC) database which contains information on annual average daily traffic (AADT), road layout, and footpath presence and dimensions. From this database, we extracted data on 180 observations (each observation is a two-lane two-way urban road section that has footpaths). In Hong Kong, the roadway geometric standards are: minimum total lane width of 5.4 m; minimum total footpath width of 1 m, and the total roadway width range of 9–14 m. These limits were used as a basis for setting the facility width constraints in our optimization formulation. Speed limits for the sampled road segments are all 50 km/h (a typical speed limit for urban roads in Hong Kong). **Figure 1** depicts the layout of a typical urban two-lane road in Hong Kong. In addition, data were obtained on the roadway geometric features including horizontal curve density (i.e., the number of curves per km), road segment length, vehicle lane width and footpath width from the Road Network database and GeoInfo Map maintained by the Hong Kong Highways Department and Planning Department, respectively. **Table 1** summarizes the data descriptions and sources. It should be noted that the widths of the footpaths on the two sides are not necessarily the same. Therefore, a variable DFW was defined to denote the difference in width between the footpaths on the two sides. Crashes were mapped to the 180 road segments considered using the Geographical Information System (GIS) technique. There are more than 1,500 traffic counting stations in the Hong Kong Annual Traffic Census system, for the purposes of transport planning. In particular, these 180 stations (widely and evenly distributed across the city) were selected based on the cross-sectional characteristics (i.e., the two-lane road with footpaths) of their corresponding road segments. At the 180 road segments over the five-year period (2011–2015), there were 3,088 FSI crashes (of these, 1,052 involved pedestrians and 2,036 involved in-vehicle occupants), and 15,992 slight injury crashes (of these, 2,956 involved pedestrians and 13,036 involved in-vehicle occupants).

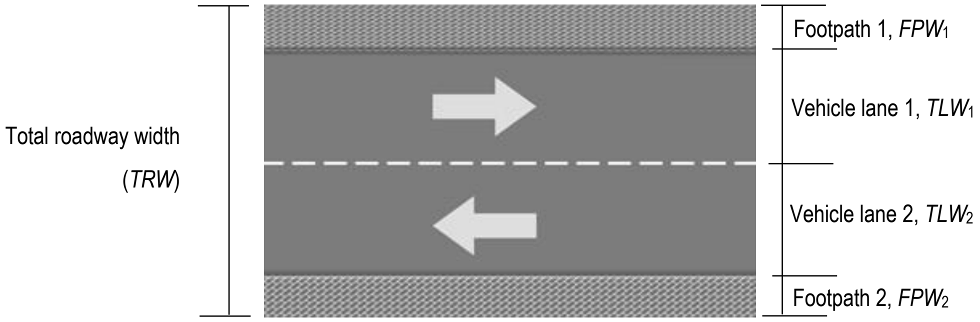


Figure 1. Illustration of a typical urban two-lane road space with footpaths

In **Table 2**, (the distribution of casualty count by casualty victim type and injury severity), it is observed that of the pedestrian casualties, the FSI proportion (26.2%) was remarkably high. **Table 3** presents the summary statistics of the sample.

Table 1 Data sources

Category	Source	Description
Traffic	Annual Traffic Census (ATC)	Average annual daily traffic (AADT)
Crashes	Transport Information System (TIS)	Number of casualties by injury severity
Geometrics	Road Network Dataset	Road segment length, horizontal curve
	GeoInfo Map	Vehicle lane width, footpath width

Table 2 Distribution of road casualties by casualty victim type and injury severity level

Casualty Victim Type	Injury Severity Level		Overall	% of FSI
	FSI	Slight injury		
Pedestrian	1,052	2,956	4,008	26.2%
In-vehicle occupant	2,036	13,036	15,072	13.5%
Overall	3,088	15,992	19,080	16.2%

Table 3 Summary statistics of the sample (180 observations)

Variable	Min.	Max.	Mean	S.D.
Response variable				
Pedestrian FSI casualty	0	81	6	9
Pedestrian slight injury casualty	0	302	16	28
In-vehicle occupant FSI casualty	0	98	11	16
In-vehicle occupant slight injury casualty	0	420	72	69
Risk factors				
Average annual daily traffic	130	25,620	8,436	5,487.36
Road segment length (m)	41.11	11,111.07	1,128.91	1,476.40
Horizontal curve density, *HCD* (per km)	0	12.67	4.10	3.25
Total vehicle lane width, *TLW* (m)	5.40	14.00	8.20	1.81
Total footpath width, *TFW* (m)	1.00	9.60	4.71	1.73
Difference in footpath width, *DFW* (m)	0	3.60	0.55	0.62

Table 4 presents the safety cost estimates that were used in the analysis. In 2019, the safety costs of fatality, severe injury, and slight injury were 61.3 million HK$, 6.5 million HK$, and 0.19 million HK$, respectively. Fatal and severe-injury crashes constituted 4.7% and 95.3%, respectively, of FSI crashes. Therefore, the weighted average safety cost of an FSI crash was calculated as:

HK$61.29(4.7%) + HK$6.45(95.3%) = 9.02 million HK$.

With regard to the agency costs of construction and maintenance, in this paper, we consider the carriageway lane pavement material as asphaltic concrete and the footpath material as concrete bricks. This is consistent with the design of most of such roadway facilities in Hong Kong (Hong Kong Planning Department, 2016). We, therefore, used estimates of the unit cost of construction and maintenance of these materials from the city’s database (Hong Kong Highways Department, 2017; Hong Kong Legislative

Council, 2000). The life cycle cost of each material type was calculated using an analysis period of 20 years, and a discount rate of 5% consistent with guidelines in the literature (Walls and Smith, 1998). **Table 5** presents agency cost estimates based on updated Construction Cost Indices (Hong Kong Civil Engineering and Development Department, 2019).

Table 4 Safety unit cost per casualty severity (year 2019)

Injury severity	Safety cost (million HK$)
Fatal	61.29
Severe injury	6.45
Fatal+severe injury (FSI)	9.02
Slight injury	0.19

Table 5 Agency costs for vehicle lane and footpath (year 2019), HK$/m^2

Cost item	Vehicle lane (Asphaltic concrete)	Footpath (Concrete brick)
Construction cost	270,000	158.4
Maintenance cost	1,294.8	106.1

4. RESULTS AND DISCUSSION

4.1 Safety performance function

Table 6 presents the results of parameter estimates of the random-parameter negative binomial regression models used to develop the safety performance functions. In general, the developed models provide good fit to the data, and the signs of the parameter coefficients were found to be intuitive and statistically significant at a 1% level of significance (with the exception of two variables that were found to be significant at 5% and 10% level of significance). The developed safety performance functions are:

$$\mu_{\text{FSI,Pedestrian}} = \exp\,(0.418 + 7.43 \cdot 10^{-5} \cdot AADT + 0.265 \cdot TFW - 0.092 \cdot TLW$$
$$+ 2.1 \cdot 10^{-4} \cdot Length - 0.094 \cdot HCD)$$

$$\mu_{\text{slightly-injured,Pedestrian}} = \exp\,(2.06 + 8.20 \cdot 10^{-5} \cdot AADT + 6.5 \cdot 10^{-5} \cdot Length + 0.171 \cdot TFW$$
$$- 0.105 \cdot TLW - 0.095 \cdot HCD)$$

$$\mu_{\text{FSI,in-vehicle occupant}} = \exp\,(1.040 + 6.31 \cdot 10^{-5} \cdot AADT + 0.047 \cdot TFW$$
$$+ 5.3 \cdot 10^{-4} \cdot Length - 0.068 \cdot HCD)$$

$$\mu_{\text{slightly-injured, in-vehicle occupant}} = \exp\left(2.739+7.80\cdot10^{-5}\cdot \text{AADT} + 0.089\cdot TFW + 3.8\cdot10^{-4}\cdot Length - 0.051\cdot HCD\right)$$

Table 6 Results of parameter estimates of random parameter models

Variable	Pedestrian		In-vehicle occupant	
	FSI	Slight injury	FSI	Slight injury
Constant	0.42	2.06**	1.04	2.74**
Std. of constant				0.42**
AADT	7.43×10^{-5}**	8.20×10^{-5}**	6.31×10^{-5}**	7.80×10^{-5}**
Road segment length	2.10×10^{-4}**	/	5.30×10^{-4}**	3.80×10^{-4}**
Std. of road segment length			1.60×10^{-4}**	1.40×10^{-4}**
Horizontal curve density, HCD	–0.094**	–0.095**	–0.068*	-0.051**
Total vehicle lane width, TLW	–0.092^{m}	–0.105*	/	/
Std of TLW	0.070**	0.086**		
Total footpath width, TFW	0.265**	0.171**	/	0.089**
Std. of TFW		0.056**		
Dispersion parameter	1.434**	1.733**	1.295**	2.873**
		Goodness of fit		
Unrestricted loglikelihood	-480.93	-659.45	-572.80	-908.56
Restricted loglikelihood	-507.61	-684.26	-617.77	-950.32
Loglikelihood ratio test	53.36**	49.62**	88.94**	83.52**

*m. Marginally significant (or, significant at 10% level); * Statistically significant at 5% level; ** Statistically significant at 1% level; / = Insignificant. Std = standard deviation of the random parameter.*

In all the developed models, the traffic volume, ***AADT*** was found to influence significantly, the number of casualties at 99% level of confidence. It observed that an increase in the traffic volume is strongly associated with a significant increase in the number of pedestrian (FSI and slight injury) crashes as well as the number of in-vehicle occupant (FSI and slight injury) crashes. A longer road segment length was found to be generally associated with increased levels of pedestrian (FSI only) as well as in-vehicle occupant (both FSI and slight injury) casualty crashes, at 99% level of confidence, albeit in a non-linear manner. Such findings are in line with those of previous studies regarding the safety effects of traffic volume and road segment length (Zhao et al., 2019; Green et al., 2011; Paulozzi, 2006; Noland and Quddus, 2004). With regard to the effect of road alignment, an increase in horizontal curve density was found to be correlated to fewer casualties (this was observed in all developed models); this was found to be significant at 5% significance level, which is consistent with past research (Lamptey, 2004; Labi, 2011). It is worth mentioning that in some other studies, the result has been to the contrary. For example, a few past studies for major roads in Hong Kong had found little or no evidence of relationships between road curvature and crash frequency (Zeng et al., 2016; Pei et al., 2016, 2012), and Elvik (2019) indicated that increased number of curves for the road segment could lower the crash rate. Such seemingly untuitive relationships identified in these few past studies, could be result of risk compensation.

4.1.1 Effect of vehicle lane width

Table 6 presents the safety effects of the vehicle lane width, ***TLW***. An increase in ***TLW*** was found be generally associated with fewer pedestrian FSI crashes, and this variable was found to be significant at the 10% level of significance; for pedestrian slight-injury crashes, ***TLW*** was found to be significant at 5% significance. However, no statistically significant evidence was found regarding the relationship between ***TLW*** and the number of in-vehicle occupant casualties. This is consistent with the findings of previous studies which had established that wider vehicle lanes contribute to improved pedestrian safety (because the extra space serves as a buffer between pedestrian and vehicular traffic) (Chen et al., 2019; Tang et al., 2018; Wu et al., 2015; Park et al., 2012; Chimba et al., 2010). A few studies have suggested that beyond a certain limit, an increase in total traffic road width could possibly increase the crash risk (Mohamed et al., 2013). Tulu et al. (2015, 2013) explained that this could be due to the effects of lane width on drivers' perception and driving speed. In this paper, however, the range of lane widths was not large enough for such risk compensation effects to be manifest.

4.1.2 Effect of footpath width

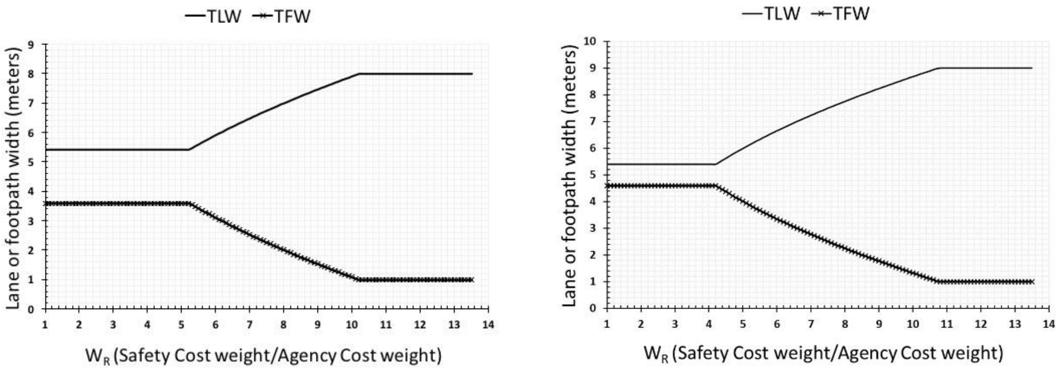
The footpath is a key pedestrian facility which promotes walkability and if well designed, could reduce vehicle-pedestrian conflicts and crashes, improve pedestrian accessibility, and create a comfortable and safe walking environment (Sze and Christensen, 2017; Oxley et al., 2004). As shown in **Table 6**, an increase in $\boldsymbol{TFW}$ is correlated to an increase in both pedestrian (FSI and slight injury) and in-vehicle occupant (slight injury only) casualties at the 1% level. Initially, this may seem unintuitive. However, wider footpaths generally accommodate or serve higher pedestrian traffic. Therefore, an increase in pedestrian casualty could be attributed to the increase in pedestrian exposure (Sze et al., 2019a). Thus, the crash count or footpath width can be normalized using the pedestrian count before incorporation into the modeling process. However, in this study, pedestrian count data were not available. In future work, with comprehensive vehicle and pedestrian flow data, it will be worth exploring the interaction between the flow and road geometry. The model developed in this paper uses data from roads with wide footpaths typically in the Central Business District areas where roadside pick-ups, drop-offs, and loading/unloading are very frequent (Sze and Wong, 2007). Therefore, with higher levels of pedestrian traffic, which translates into more frequent incidences of errant pedestrian behavior (such as reckless crossing), thus increasing pedestrian crash frequency (Kim et al., 2017; Granié et al., 2014). This observation is consistent with the findings of previous studies that determined the risks of vehicle-pedestrian crashes and pedestrian injuries to be higher in business and commercial areas (Hu et al., 2020; Kim et al., 2006; Noland and Quddus, 2004). Future research could seek objective and subjective data on pedestrian behavior to investigate further, the relationships among the footpath width and the pedestrian-vehicle conflicts and crashes.

4.2 Optimal width allocation

This section presents the results of the optimization of width allocation of vehicle lanes and footpaths given a fixed total road width ($\boldsymbol{TRW}$). The possible values of $\boldsymbol{TRW}$ range from 9 to 14 m in accordance with the space available for typical two-lane roads in Hong Kong. To accommodate the difference in importance levels attached to the safety cost and agency cost in the agency's decision making, a variety of weight combinations of these costs is investigated in this paper. **Figure 2** presents the relationship between optimal solutions (optimal widths of the traffic and lane and footpath, for different combinations of the total roadway width and the relative weight between agency and user cost.

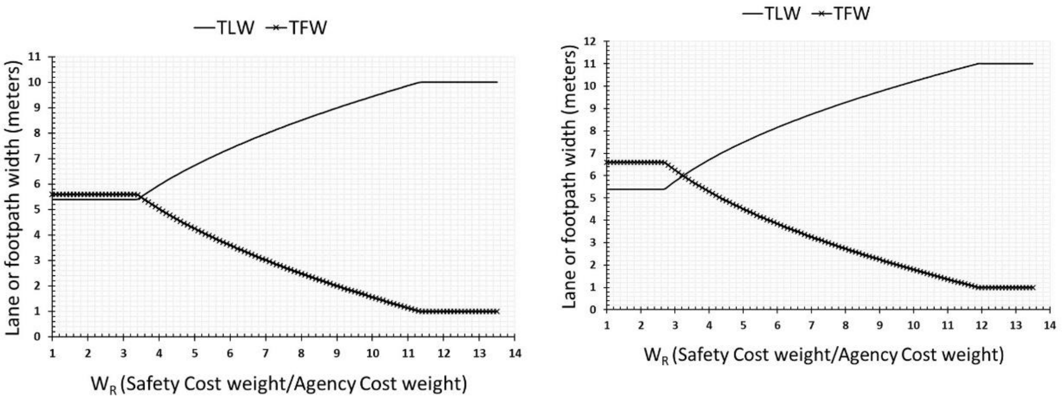
As shown in (**Figure 2 (a)** to **(f)**), when the agency considers user (safety) cost and agency cost as equally important (i.e., $\boldsymbol{W_R}$ = 1), the optimal $\boldsymbol{TLW}$ is 5.4 m which, regardless of $\boldsymbol{TRW}$, is the minimum feasible lane width specified by the road authorities in Hong Kong. In other words, the road vehicle lane width should be set at the minimum possible width, and the remaining road space should be allocated to the footpath. This can be expected because the unit construction cost and maintenance cost of vehicle lanes (paved with asphalt) substantially exceeds those of the footpath (paved with concrete brick), despite the reductions in pedestrian casualties when vehicle lanes are wider. Therefore, when vehicle lane width increases, the corresponding increase in the agency cost is not offset by the corresponding safety cost reduction (which is only marginal); therefore, the total life-cycle cost increases.

On the other hand, when a very large weight is assigned to user (safety) cost, the optimal $\boldsymbol{TFW}$ is 1.0 m (i.e., the minimum value specified in constraint), regardless of $\boldsymbol{TRW}$. In other words, the minimum width should be assigned to the footpath, and the remaining road space should be allocated to the vehicle lane. This is because in this case, the increase in agency cost attributed to increased vehicle lane width is offset by the safety cost reduction attributed to the reduction in pedestrian casualty. The tipping point (also referred herein as the critical point or the crossover point) of $\boldsymbol{W_R}$, that is, the point at which the optimal $\boldsymbol{TFW}$ exceeds the optimal $\boldsymbol{TLW}$, clearly varies with $\boldsymbol{TRW}$. As shown in **Figure 3**, the critical $\boldsymbol{W_R}$ decreases gradually from 5.3 when $\boldsymbol{TRW}$ is equal to 9 to 1.7 when $\boldsymbol{TRW}$ is equal to 14 ($\boldsymbol{W_R}$ = 4.3, 3.4, 2.7 and 2.2 when $\boldsymbol{TRW}$ = 10, 11, 12 and 13 respectively). In other words, if a larger weight is assigned to user (safety) cost and the road space is not too restricted, then the tipping or crossover point of the optimum width allocation occurs earlier.



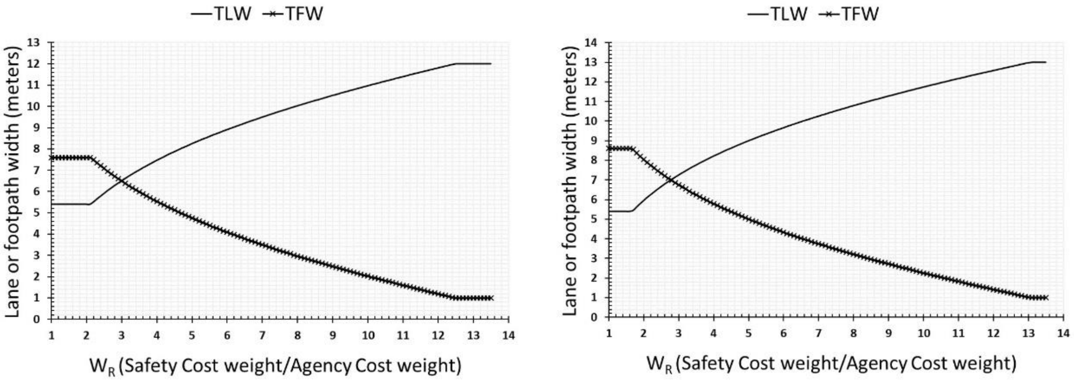
(a) TRW = 9 m

(b) TRW = 10 m



(c) TRW = 11 m

(d) TRW = 12 m



(e) TRW = 13 m

(f) TRW = 14 m

Figure 2 Optimal allocations of total road width to vehicle lane and footpath

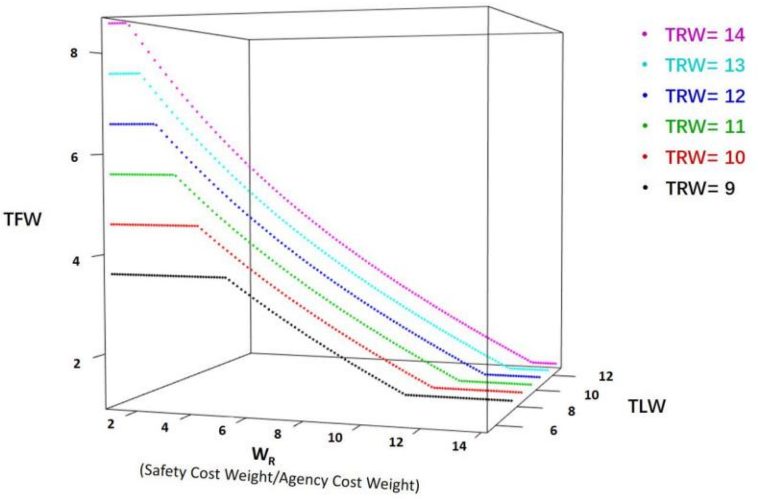


Figure 3. Relationship between total footpath width, total vehicle lane width and safety-agency relative weight

4.2.1 Vehicle lane width

The optimal ***TLW*** determined in this paper was compared with the state of practice, that is, the minimum carriageway width of 7.3 m for two-way two-lane urban roads in Hong Kong as specified in the city's design manual. For a narrow two-lane road (e.g., ***TRW*** is less than or equal to 11 m) (**Figure 2)**, a carriageway width of 7.3 m corresponds to a safety-to-agency cost ratio $\boldsymbol{W_R}$ of 5.8 to 8.6. In other words, the width allocation policy that is used currently means that the Hong Kong road agency implicitly considers user safety to be at least 5.8 times more important than the construction (agency) cost. This probably reflects the mission of the city authorities toward safety promotion, and the fact that the roads investigated in this study are located in very busy urban areas where on-road activities are more prevalent. In contrast, at urban location situations where there is adequate space (***TRW*** is greater than 11 m), the safety-to-agency cost ratio $\boldsymbol{W_R}$ inherent with the agency's design policy of 7.3m wide lanes, reduces to 3.0 – 4.7. As shown in Figure 2c, d, e, and f, the current agency design policy of 7.3 m ***TLW***, translates into implicit weight ratios ($\boldsymbol{W_R}$) of: 8.6, 7.1, 5.8, 4.7, 3.8, 3.0, for the given fixed ***TRWs*** of 9, 10, 11, 12, 13 and 14 meters, respectively.

These road space situations are generally encountered at new development and redevelopment areas. The agency may place a higher importance to the financial outlay for road construction/maintenance and therefore, by default, a corresponding relatively lower importance to road safety. It may be noted that unlike construction costs, safety benefits are less direct and more intangible, from the agency's perspective. In any case, the above findings seem consistent with the mission of "vision zero" which is the elimination of fatalities and severe injuries (Road Safety Council, 2019).

Therefore, the overall observation is that, based on the existing practice of width allocation in the design manual of Hong Kong, the implied weight that corresponds to the Hong Kong agency practice suggests that the agency places higher weight on the safety cost compared to agency cost. In contrast, in a past study carried out using rural highway data from Indiana, USA, researchers determined that the agency implicitly places a higher weight for the agency cost compared to the user cost of safety (Labi et al., 2017). Such a contradictory finding could be attributed to the differences in the location context (urban vs. rural) and hence, the problem context (lane vs. shoulder in the earlier study, and lane vs. footpath in the current study), and the realization that shoulders and footpaths use different construction methods and building materials with different implications on construction and maintenance costs over their life cycle.

4.2.2 Footpath width

To promote walkability and pedestrian-friendliness, cities strive to ensure that their pedestrian infrastructure including footpaths, are well-planned and designed. This is important at compact cities such as Hong Kong where walking serves as the primary mode for short-distance trips to access public transport and other essential urban services (Sze and Christensen, 2017). In accordance with the Transport Planning and Design Manual of Hong Kong (Hong Kong Planning Department, 2016), the footpath can be divided into three zones: the Through Zone, Street Furniture, and Greening Zone. The Through Zone serves pedestrians' through movements and building access. Street

Furniture includes signposts, bollards, street lamps, railings, and bus stations. The Greening Zone is for landscape plants and other amenities that enhance the visual appeal of the walking environment. The minimum widths of the above three zones are specified per adjacent land use and pedestrian flow. For example, the minimum width for a footpath at commercial and business areas is 7.0 m, and that of residential areas is 4.5 m, given that pedestrian flow of the latter is lower (i.e., less than 60 pedestrians per minute). However, it is difficult to achieve these targets in Hong Kong due to space constraints.

This paper establishes the optimal width allocations of vehicle lanes and footpaths. Using Hong Kong as a case study, it was found that for an urban two-lane road with $\boldsymbol{TRW}$ of 10 m, the optimal $\boldsymbol{TFW}$ is 4.6 m (e.g., 2.3 m on either side) when $\boldsymbol{W_R}$ is set at 1.0m – 4.0m. This is generally not far from the recommended minimum widths for the through zone of footpath (e.g., 2 m for each side) in the residential zones. A further increase in the footpath width is needed to allow for the addition of the street furniture and green zones, both of which are expected to further enhance the walking environment for pedestrians (Transport Department, 2019). Nevertheless, it seems only feasible to apply both of the required standards in the area with less severe land constraints. In most of the cases, agencies in Hong Kong may face the trade-offs between implementing the lane width standard and footpath width standard due to the scarce land resources. Under such circumstances, the results from this study can help support design decisions by presenting an optimal solution for a given safety-agency cost weight ratio and a given amount of available road space, $\boldsymbol{TRW}$. In addition, for developed areas, appropriate pedestrian schemes, such as pedestrian zone, traffic calming, and road closure, can be implemented to improve the area-wide pedestrian environment.

5. SUMMARY AND CONCLUDING REMARKS

This paper is motivated by the severe constraints on roadway space in crowded megacities such as Hong Kong vis-à-vis the need for safe, efficient, and cost-effective movement of pedestrians and vehicles in these cities. The paper addressed the specific context of a two-lane urban road space allocation to two main cross-sectional elements: the lane width and the footpath width. The paper also duly recognized that the allocation of space should be influenced by the differences in construction and maintenance (C&M) costs of the paving materials for these elements, the relative weight between the agency (C&M) cost dollar and user (safety) cost dollar, and the available road space (width). A formal optimization problem was formulated with the objective of minimizing the total life-cycle cost, space constraints, and the decision variables were the widths to be allocated to each of the two cross-sectional elements.

The study began with the calibration of models to predict the number of pedestrian and in-vehicle occupant casualties, using the random-parameter negative binomial regression approach. The following explanatory factors were considered: vehicle lane width, footpath width, horizontal alignment and vehicle traffic flow. Using the developed models, the sensitivities of pedestrian and in-vehicle casualties to the vehicle lane and footpath widths, were analyzed. This was followed by calculations of the safety cost and agency cost functions for different combinations of the road vehicle lane and pedestrian footpath widths. Furthermore, a relative weight was assigned to safety and agency costs to represent the agency's preferences regarding these two performance indicators. The optimization was carried out for different relative weights to accommodate any possible changes in the agency's preferences in the future.

Considering the vehicle lane width, horizontal alignment, and vehicle traffic flow, the model results were intuitive, and these variables were statistically significant. The optimization model results suggest that when safety and agency costs are considered equally important, the vehicle lane width should be set at minimum width specified in the agency's standards (i.e., 5.4 m) and all remaining road space should be allocated to the footpath. This result is expected because the construction and maintenance costs of the footpath (recycled concrete brick paving) were substantially lower than that of vehicle lane (asphaltic concrete paving). In contrast, when a very high weight was assigned to safety cost (which implies a stronger incentive to improve safety compared to agency spending), the optimal footpath width was equal to the minimum width specified in the agency's standards (i.e., 1 m). This is because the regression model indicated no favorable safety effect with increasing footpath width. Between the two extremes of W_R, there is a specific range of W_R in which the transition of the optimal lane width from its minimum value of 5.4 m to the maximum value (TRW–1) m, was observed. Interestingly, these transitions occur at lower values of the W_R with wider roadways. As depicted in the relationship between recommended design specifications, optimum allocation policy, and the relative weights of safety to agency cost, the agency's design policy of 7.3m lane with was found to translate, albeit implicitly, into much higher preference of the agency toward safety compared to agency cost, particularly where the roadway has narrow overall space. Coincidentally, this observation is consistent with the "vision zero" target of the Hong Kong government.

The paper, hopefully, has opened up several avenues for future inquiry in this area. It may be considered useful, as in this paper, to carry out optimization to allocate the roadway width to its users (vehicles and pedestrians) in a balanced manner. Nevertheless, in certain parts of compact cities including Hong Kong, there is probably a limit to the overall effectiveness of such allocation optimization, due to external factors such as very high pedestrian volumes and building access in areas of dense building development. Therefore, future research in this area could examine the extreme conditions that will warrant the implementation of other initiatives which include pedestrian-friendly facilities such as pedestrian-only streets and traffic calming. Further, at new development and redevelopment areas, the "three-zone" footpath design concept can be considered for implementation. In that case, a buffer facility could be provided to separate the pedestrian and vehicular traffic. These initiatives, which are valuable components of a walkable city, can significantly enhance the safety, environment, and quality of service for pedestrians.

Another limitation of the study, is the rather limited number of built environment attributes that were considered in the analysis. There exist other variables that may impact safety but were excluded in the SPFs in this paper due to lack of data. These include the geometric features of the urban roadway, access density (number of driveways or access points per mile), and the design or operating speed. If data are available on these factors, that could open up areas for future research in this domain. In addition, data on pedestrian exposure (flow) and pedestrian behaviors could be collected where possible, and incorporated in the model to avoid bias associated with different footpath widths and pedestrian casualty relationship. Further, when the requisite data are available, it will be worth exploring the impacts of types of land use and built environment, and pedestrian activities on the space allocation outcome. This paper’s analysis could also be extended to a network level, similar to the work of Murillo-Hoyos et al. (2016), to identify which of all footpath sections in a given city deserve to be selected for widening, under constraints of a budget dedicated to this purpose. Finally, other indirect or intangible costs including improved air quality, health, and quality of living could be monetized using information from the literature (Sze and Christensen, 2017; Daniel et al., 2016; Stevens and Salmon et al., 2014) and considered in the life-cycle cost-based optimization of this paper. Last but not the least, a more comprehensive optimization framework for the width allocation of urban roads could be proposed in the future taking into account other social costs derived from the decreased pedestrian level of service (narrow footpath) or/and congestion (narrow vehicle lane).

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