A COMPREHENSIVE LITERATURE REVIEW DETAILING THE METHODS FOR SETTING SPEED LIMITS IN URBAN AREAS

Literature Review

PROJECT SPR 827

RESEARCH

Oregon Department of Transportation

A COMPREHENSIVE LITERATURE REVIEW DETAILING THE METHODS FOR SETTING SPEED LIMITS IN URBAN AREAS

Literature Review

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by

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16. Abstract
Many cities in Oregon are requesting a comprehensive review of speed zoning guidelines and existing procedures for streets with high volumes of active travelers. Cities are proposing alternative speed zoning guidelines that are starkly different from existing guidelines based on the 85th percentile speed distribution. The alternative guidelines and criteria for setting speed zones have not been thoroughly studied or evaluated yet. This report presents a comprehensive review of literature pertaining to factors which may influence operating speeds, speed limits compliance, and relationships between speed and crash frequency and/or severity. The focus is on urban areas and roadways with a high percentage of active users. This review is intended to support research and policy analysis that examine alternate criteria for setting speed zones on roadways with a high percentage of active travelers.

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APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					**LENGTH**		
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	Meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	Meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
		AREA					**AREA**		
in^2	square inches	645.2	millimeters squared	mm^2	mm^2	millimeters squared	0.0016	square inches	in^2
ft^2	square feet	0.093	meters squared	m^2	m^2	meters squared	10.764	square feet	ft^2
yd^2	square yards	0.836	meters squared	m^2	m^2	meters squared	1.196	square yards	yd^2
ac	acres	0.405	Hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	kilometers squared	km^2	km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME					**VOLUME**		
fl oz	fluid ounces	29.57	milliliters	ml	ml	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	Liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
~NOTE: Volumes greater than 1000 L shall be shown in m^3.									
		MASS					**MASS**		
oz	ounces	28.35	Grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)					**TEMPERATURE (exact)**		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C	°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

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1.0 INTRODUCTION

Many cities in Oregon are requesting a comprehensive review of speed zoning guidelines and existing procedures for streets with high volumes of active travelers. Cities are proposing alternative speed zoning guidelines that are starkly different from existing guidelines based on the 85^{th} percentile speed distribution. Existing methods must be reevaluated as well as the pros and cons of alternative procedures and criteria. Speed zoning guidelines should be balanced, reasonable, and provide safe speed zones for all users.

This report presents a review of literature pertaining to factors that may influence operating speeds. Current US guidelines for speed zoning, many based on the 85^{th} percentile of operating speeds are reviewed as well as adjustment factors and alternative approaches. Current recommendations regarding data collection guidelines in terms of number of observations and equipment are also included. The relationships among speed and crash frequency, and crash severity are also reviewed. The literature review includes US based approaches, guidelines, and research results but also international best practices, research results, and alternatives views regarding speed zoning.

Throughout the document, an effort has been made to link literature review findings to their potential implications for speed zoning guidelines for roadways with a high percentage of active users.

1.1 SPEED DEFINITIONS

This report includes many international references. Most of the research papers and references, even many from the US, do not distinguish among statutory speed limits, speed zoning, and posted speed limits. These terms are used loosely and interchangeably in most studies to indicate the speed limit that can be enforced at a given roadway or location.

1.2 ORGANIZATION OF THE INTERIM REPORT

This report is organized into eight chapters. Chapter two presents an overview of factors that influence operating speed. Chapter three discusses the relationship between speed and crashes. Chapter four focuses on compliance. Chapter five reviews speed management concepts. Chapter six summarizes current speed zone guidelines. Chapter seven reviews alternative speed zoning approaches. Chapter eight ends with conclusions. References and one appendix summarizing key research papers are also included in the report.

2.0 FACTORS INFLUENCING OPERATING SPEEDS

There are many factors that can potentially affect driver selection of operating speed. To facilitate the presentation of the research results this chapter tries to divide them into distinct subsections. However, many factors are confounded, the reader should note that some overlap among explanatory variable types in the following subsections is unavoidable.

2.1 POSTED SPEED LIMIT

Fitzpatrick et al. (2001) investigated the relationship between geometric, roadside, and traffic control variables and operating speed on four-lane suburban arterials with speed limits ranging from 30 to 45 mph in Texas. A total of 19 sites located on horizontal curves and 36 sites located on straight section were selected for the study. Vehicle operating speeds at the 55 sites were collected using laser guns connected to laptop computers. The analysis of speeds at sites located on horizontal curves indicated that posted speed limit, deflection angle, and access density significantly affected operating speeds. For the straight sections, only posted speed limit was found to affect operating speed significantly.

Because posted speed limits are frequently based on the observed 85^{th} percentile operating speed, there is some concern with using it as a variable in this type of analysis. To further study the relationship between posted speed limit and operating speed, *Fitzpatrick et al. (2001)* analyzed the data without including the posted speed limit variable and it was found that the presence of medians and roadside development became significant variables for the horizontal curve sites. Lane width was the significant variable for the straight section sites. One additional meter (3.3 foot) in lane width is expected to increase the average operational speed by 15 km/h (9.4 mph). In all cases, stronger relationships were found by including the posted speed limit in the analysis.

Himes et al. (2013) also explored the impact of including and removing posted speed limit as an independent variable to predict operating speeds. Vehicle operating speeds were collected on both urban and rural two-lane highways with mean posted speed limits and operational speeds between 65 and 70 mph in Pennsylvania and Virginia. Speed data was collected using on-pavement sensors at 79 locations. Posted speed limit explained eighty-two percent of the variation in operating speed. The authors of the research suggested that posted speed limit should be included as an exogenous variable to reduce bias of variables related to roadway geometry.

Islam et al. (2014) analyzed a case study in Edmonton, Canada where the posted speed limit was reduced from 50 km/h (30 mph) to 40 km/h (25 mph) in six urban, residential communities to study the effects of reducing the posted speed limit on vehicle speeds. A before and after method was chosen with the ‘before’ period as one month prior to the reduction and the ‘after’ period consisting of the following six months. Three communities with similar traffic and environmental conditions were chosen as control sites. Seven months of speed data were collected on a 24 hour-a-day and seven day-a-week basis using Vaisala Nu-Metrics Portable Traffic Analyzers, model NC200. Only vehicles in free-flow speed were used in the analysis. Free-flow was defined as a headway of more than two seconds as Edmonton advises drivers to follow a two second headway rule under normal driving conditions. Weather data was matched to the speed data and records during adverse weather were removed from the analysis. The overall result indicated lowering the posted speed limit was effective at reducing mean vehicle speeds (3.86 km/h [2.4 mph] and 4.88 km/h [3.03 mph] three and six months post treatment, respectively). Mean speeds at untreated comparison sites showed a consistent increasing trend. Speed variance was also reduced for all combinations of time of day, day of week, road classification, and vehicle type except for heavy vehicles. In terms of road class, speed limit reduction was found to be more effective in reducing vehicle speed on local roads than on collector roads. The posted speed limit reduction was accompanied by a variety of educational and enforcement measures such as media campaigns (TV, print, online, etc.), speed display boards, community speed programs. The results suggest that speed limit reductions plus integrated educational and enforcement activities are expected to reduce overall average speed and speed variability.

A before and after study conducted on vehicle speeds in Boston indicated the proportion of vehicles exceeding 25, 30, and 35 mph slightly decreased after the default speed limit was lowered from 30 mph to 25 mph beginning January 2017, although there were no significant changes in mean and 85th percentile speeds *(Hu & Cicchino, 2018)*. At comparison sites in Providence where the speed limit did not change, proportions of vehicles exceeding 30 and 35 mph slightly increased during the study period. Posted speed limit signage was absent at all data collection sites, but the reduction in Boston had been publicized by a press release on several news outlets and various forms of advertisements during the first year.

Gargoum et al. (2016) used data collected over a five-year period from nearly 600 urban arterial and collector road segments with speed limits ranging from 20 to 50 mph in Edmonton to identify factors that affect operating speed and compliance with speed limits. Compliance was divided into five categories to help the model differentiate between vehicles violating speed limits by different margins since the City of Edmonton typically specifies a threshold of 10 or 15 km/h (6 or 9 mph) over the posted speed limit before issuing a citation. The categories ranged from fully compliant speeds to exceeding the posted speed limit by 20 km/h (12 mph) or more. Geographic and design features were recorded as well as posted speed limits. Results of the analysis showed a positive correlation between the posted speed limit and compliance levels. The presence of medians, significant on arterials only, increase the probability of a speed limit violation. Other factors such as number of lanes and on-street parking were significant but had different signs for arterials and collectors. It should be noted that variables associated to educational efforts and enforcement activity were not considered in the analysis because the necessary datasets were not available.

A review of speed limit studies is presented by a meta-analysis of the relationship between changes in speed limit and changes in mean traffic speed *(Elvik 2012)*. From Figure 1 it is clear that a 10 km/h speed limit increase or decrease will not result, on average, in an average 10 km/h mean traffic speed limit increase or decrease respectively; on average the mean speed will be reduced approximately by 3 km/h and the mean speed will be increased approximately by 2 km/h respectively. There is a lot of variability around the fitted trend line.

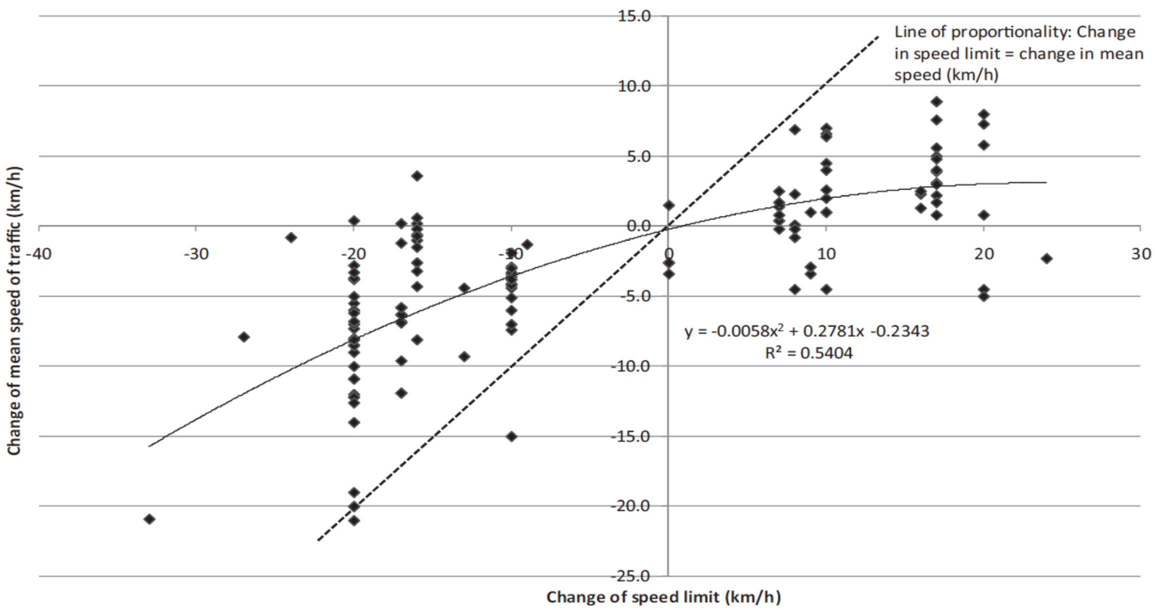

Figure 2.1: Effects of changes in speed limit on the mean traffic speed (reproduced from *Elvik, 2012*)

2.2 GEOMETRY AND ROADSIDE CHARACTERISTICS

Controlling for speed limit allows the influence of street characteristics on driving speeds to be explored in more depth. *Dinh & Kubota (2013a)* observed operating speeds on tangent sections of urban residential streets in Japan with a 30 km/h (20 mph) speed limit to develop models to predict 85th percentile and mean operating speeds. Using continuous speed data from STALKER ATS radar guns, 5359 individual speed profiles for 85 street sections were analyzed in relation to street alignment, cross-section variables, access density, roadside object density, and land use development. The length of the street section between two intersections and carriageway width were both found to positively correlate with mean and 85th percentile speeds. Roadside object density was found to be negatively correlated with speeds. Other significant variables with positive signs were number of lanes and the presence of sidewalks.

Thiessen et al. (2017) attempted to explore relationships of road features and operating speeds for urban tangential road segments in Edmonton, Canada. A total of 249 arterial and collector road segments with speed limits of 40 to 100 km/h (25 to 62 mph) were analyzed. A Vaisala Nu-Metrics Portable Traffic Analyzer was used for the data collection which occurred between 2009 and 2013. Only vehicles with a headway of 2 seconds or more was used for analysis. There was an average of 80,752.4 observations per site. The researchers found the effects of certain road elements differed between road classifications and the two variables that stood out were median width and bus stops (positively correlated with arterials and negatively correlated with collectors). Posted speed limit was significantly positively associated with operating speed for both the arterial only model and the combined arterial and collector model. Roadside treatment (as a localized proxy for land use) was found statistically significant in the collector only model with low density areas experiencing the highest operating speeds. Sidewalks that were farther away from the road were associated with higher operating speeds. Segments with monolithic sidewalks on both sides of the road were associated with lower operating speeds. Pedestrian crossings were associated with lower operating speeds and the presence of bike lanes correlated to higher operating speeds in the combined model. Operating speeds also seemed to decrease as access density increased while longer segments were associated with higher operating speeds. A full list of significant variables is provided in Appendix A.

In addition to the posted speed limit, *Gargoum et al. (2016)* also tested the effects of land usage; vertical and horizontal alignment; the presence of medians, shoulders, bus stops, and bike lanes; how many sides of the road had parking; and the number of lanes on speed limit compliance. Increased number of lanes and parking were found to positively correlate with speed limit compliance on arterial roads and negatively correlate with compliance levels on collector roads. Presence of vertical alignments, medians, and shoulders were negatively associated with compliance for both road classifications. Land use was also found to affect compliance with industrial areas seeing lower levels than residential for collector roads. For arterial roads, commercial and agricultural areas had lower levels of compliance than direct control areas.

Speed dispersion is also an important consideration when setting reasonable and safe speed limits. *Bassani et al. (2014)* sought to explore the relationships between geometric variables, mean speed, and speed dispersion on urban arterial and collector roads with speed limits of 30 to 70 km/h (20-45 mph) in northern Italy. Data was collected using a laser speed gun and high speed digital video from each lane of 16 different road sections. Of the variables considered, lane position and number of traveled ways influenced mean speed the most. Speed dispersion was increased by the presence and width of shoulders, the presence of bus and taxi lanes, traffic calming devices, and parking lanes. The presence of sidewalks and pedestrian crossings made a significant contribution to a reduction in speed dispersion.

While most research conducted has focused on predicting mean or 85th percentile speeds, a more holistic picture can be seen by disaggregating the data and examining the distribution of speeds throughout specified speed categories. *Eluru et al. (2013)* estimated models for speed distribution profiles of urban local and arterial roads where speed limits ranged from 40 to 50 km/h (25 to 30 mph) in Montreal. Speed and volume hourly data were collected using traffic sensors for the 49 local roads and 71 arterials analyzed. Results indicated the number of lanes increased the proportion of vehicles in higher speed categories for both local roads and arterials. Speed distributions on local roads were negatively correlated with the presence of parking and positively correlated with both the number of sidewalks present and the presence of bicycle routes.

Table 2.1 summarizes the factors found to influence operating speeds. The direction of arrow indicates the direction of correlation. Variables indicated with * were found to be significant only when excluding posted speed limit from the model. Also, of note, *Bassani et al. (2014)* studied how the selected variables affected speed dispersion instead of their direct effects on speed and *Gargoum et al. (2016)* examined the selected variables' effects on speed limit compliance.

2.3 ENVIRONMENTAL VARIABLES

Along with geometric features and road characteristics, road safety and operating speed can be influenced by lighting conditions. *Bassani et al. (2016)* modeled speed distributions according to sunny, cloudy, and night-time lighting conditions of urban arterial roadways where speed limits ranged from 50 to 70 km/h (30 to 45 mph) in northern Italy. Vehicle speeds were measured using laser speed guns and video cameras. Vehicle-mounted photometers measured luminance from a driver's perspective and a lux meter was utilized to measure the illuminance of the road surface. An increase in illuminance was found to increase the average value of speed distribution and deviation from mean speed in all lighting conditions. Deviations of mean speed were greatest during night-time conditions.

Sadia et al. (2018) used Structural Equations Modeling (SEM) to relate environmental, driver, and situational characteristics to driving speed. Data was collected through a combination of stated-preference surveys and driving simulations by 111 drivers. Four different situational risk/benefit scenarios were presented to each driver before they drove the simulator on four randomly selected road scenes, of which there were eight in total. The scenarios included an ordinary daily trip, a trip on a road with a high risk of enforcement, a trip on a road with a known high crash risk, and a trip in which the driver was running late for an important meeting. Driver characteristics were collected via the survey after the drivers completed their four simulated trips. Three models were estimated as follows:

- The driver-level analysis measured the effects of gender, age, and driving frequency on the latent variables of technical aversion (how drivers perceive technical tasks related to vehicle operation and maintenance), risk awareness, law awareness, and skills-safety gap (the gap between a driver's self-assessment of driving skills and their self-proclaimed driving habits). Female gender affected all latent variables such that they reduced the average and/or standard deviation of driving speed. Age over 40 reduced average speed through the risk awareness variable. High driving frequency increased average driving speed directly and increased both average driving speed and standard deviation through the skills-safety gap variable.

- The trip-level analysis added risk/benefit, design speed (which was set to either 80 or 100 km/h [50 to 60 mph]), and interaction variables (between gender, age, and number of trials completed by the driver) to those variables in the driver-level model. The risk/benefit scenarios were combined into a single latent category called Lower Speed Incentives. The crash risk and enforcement scenarios lowered the average and standard deviation of speed through the risk/benefit variable while the time-saving scenario had the opposite effect. A lower design speed reduced both average speed and its standard deviation. Being a female over 40 years of age reduced average driving speed, but this effect was reduced with progressive trials.

- The segment-level analysis added an environmental speed perception (ESP) variable to the trip-level model. Horizontal curves and increased longitudinal slopes were associated with a reduction in the value of the ESP variable. Presence of a 90 km/h (56 mph) speed limit sign decreased the ESP value, but not by a substantial amount. Driving speed of either 90 or 110 km/h (56 or 68 mph) by the surrounding simulated traffic increased the ESP value. Higher ESP values increased the average driving speed but reduced the standard deviation.

The goodness-of-fit comparison of models showed the driver-level model was within acceptable standards but the trip and segment level goodness-of-fit indicators were below expectations.

2.4 SUMMARY

There are many factors that can potentially affect drivers' selection of operating speeds. The literature review indicates that posted speed limit increases tend to increase operating speeds and speed limit decreases tend to decrease operating speeds; however, there is a lot of variability around the mean observed effects.

Factors such as geometry, roadside characteristics, and environmental factors also impact operating speeds. In many cases these factors are confounded which difficult the estimation of individual impacts and may lead to contradictory findings. In some cases there are methodological issues like for example some studies lack appropriate falsification tests when controlling for observations taken before and after speed limit changes.

Most studies are also conducted on rural or suburban roadways. In most studies, roadways have no or scant active users and/or there are variables that measure and take into account the number or even the presence of active users.

Table 2.1: Summary of some Geometric and Roadside Factors Affecting Operating Speeds.

FACTOR	AUTHOR										
	*Bassani et al. (2014)***	*Dinh & Kubota (2013)*	*Eluru et al. (2013)*		*Fitzpatrick et al. (2001)*		*Gargoum et al. (2016)****		*Thiessen et al. (2017)*		
			Arterial	**Local**	**Curve**	**Tangent**	**Arterial**	**Collector**	**Arterial**	**Collector**	**Combined**
Access density					↓				↓	↓	↓
Auxiliary lanes (bike, bus)	↑			↑					↑ (bus stop)	↓ (bus stop)	↑ (bike)
Land use					*		↓	↓	↑	↓	↑
Lane or road width		↑				↑*			↓	↑	
Medians					↑*		↓	↓	↑ (width)	↓ (width)	↑ (width)
Number of lanes		↑	↑	↑			↑	↓			
Parking	↑			↓			↑	↓			
Pedestrian Crossings	↓									↓	
Posted speed limit		controlled	↑		↑	↑	↑	↑	↑	↓	↑
Roadside object density		↓							↓ (pole) ↓ (tree)	↑ (pole) ↑ (tree)	↓ (tree)
Segment length		↑							↑	↑	↑
Shoulders	↑						↓	↓			
Sidewalks	↓	↑		↑					↑ (width)	↑ (width)	

* indicates variable was only significant after excluding posted speed limit from the model
** indicates change in speed dispersion
*** indicates correlation to speed limit compliance

3.0 SPEED AND CRASH RELATIONSHIPS

According to the National Highway Traffic Safety Administration (NHTSA) there were 1.18 traffic fatalities per 100 million VMT in 2016, of which 27% were speeding related *(NHTSA, 2017)*. The relationship between speed and road safety is an extensive topic with a growing body of research. This section reviews some key references, and as much as possible, the focus is on urban areas and active users.

3.1 SPEED AND CRASH FREQUENCY

Pilkington (2000) cites that a study by the Department of the Environment, Transport and the Regions (DETR) shows evidence of increased pedestrian safety by lowering speed limits in urban areas from 30 mph to 20 mph. The study Pilkington cites indicates a 60% reduction in traffic crashes and a 67% reduction in child pedestrian and child cyclist crashes in 20 mph zones with overall vehicle speeds lowered by 9.3 mph on average *(DETR, 1997, as cited in Pilkington, 2000)*.

Islam & El-Basyouny (2015) studied the safety effects of lowering the urban residential posted speed limit from 50 km/h (30 mph) to 40 km/h (25 mph) in Edmonton, Canada in a before and after modeling approach. Crash data for three years prior to the year the speed limits were lowered were used as the 'before' period and crash data for the three years post reduction were used as the 'after' period. Traffic volume, road geometry, and other relevant site data were collected for the 27 treatment sites and the 287 reference sites. Univariate and multivariate empirical Bayesian and full Bayesian models were tested and the multivariate full Bayesian model was chosen for the final analysis based on the goodness-of-fit criteria. Based on the model results, severe and property damage only crash rates were estimated to see a 50 % and 18% reduction, respectively. The estimated total crash rate reduction was calculated from the univariate full Bayesian model at 26% due to the accumulation of potential uncertainty in the multivariate model from the combined estimates for severe and property damage only crashes. Utilizing a multivariate full Bayes estimation method the following variables were significant and positively related to both severe and PDO crashes: length, AADT, presence of alcohol-licensed premises, and stop-controlled intersection density. Presence of street parking was significant and positively related to PDO crashes. Uncontrolled intersection density was significant and positively related to severe crashes.

Gargoum & El-Basyouny (2016) collected speed data over a five-year period from 353 different 40 to 90 km/h (25 to 55 mph) two-lane urban road segments in Edmonton, Canada and linked it to the crash frequency at each location during the same time frame. The mean average speed was 46.6 kph (29 mph) and the percentage of speed limit violators was 0.66. A structural equation modelling approach was utilized and results show that average speed, volume, segment length, medians and horizontal curves all have positive statistically significant effects on number of crashes. Shoulders, posted speed limits, bus stops, traffic volumes, segment length, and vehicle-lengths are significant positive variables that influence speeds.

Taylor et al. (2000) used crash data spanning a five-year period from 100 urban roadway sections with speed limits of 30 to 40 mph in the United Kingdom and found that increases in mean speed and speed variation were positively correlated with increasing personal injury crash frequency. The crash frequency in this study was defined as the number of crashes occurring on a given section of road per unit of time.

Wang et al. (2018) utilized high frequency GPS data to study the relationship between mean speed, speed variation, and traffic crashes on urban arterial roadways in Shanghai, China. A total of 1567 crash data records were utilized for the modeling, where 18 records were severe injury or fatal crashes with the remainder consisting of slight injury or property damage only crashes. Speed limits are not posted on urban arterials in Shanghai, but the average observed operating speeds for the segments in this study were found to range between 36 and 60.4 km/h (22 to 37 mph). After controlling for vehicle kilometers traveled (VKT), speed variation, and density of signal spacing for their average values, it was found when the mean speed increased by 1%, the expected total crash frequency increased by 0.7%. Additionally, there was a 0.74% increase in total crash frequency when speed variation increased by 1%, after controlling for the average values of VKT, mean speed, and signal spacing density.

Gitelman et al. (2017b) explored the relationship between speed and crash occurrence on non-urban road sections in Israel, accounting for traffic exposure and infrastructure conditions. Speed limits on such road sections are typically 80 km/h (50 mph). Speed data were collected by GPS for six months between February and July of 2011 and included over 30 million free-flow speed observations. Total injury crash numbers and traffic volumes from 2009 to 2011 were obtained from the Central Bureau of Statistics. Lane width, shoulder width, horizontal radius, percent of segment with vertical grade, percent of segment with safety barriers, and junction density for each road segment were taken from a 2010 road survey by the National Transport Infrastructure Company. These characteristics were used to create homogeneous groups of road segments in an attempt to control for infrastructure conditions. A model for weekday daytime (6:00-22:00) hours and a model for weekday nighttime (22:00-6:00) were developed. Both models demonstrated that the number of crashes is positively correlated with section length, traffic volume, and mean speed. Standard deviation of speed appeared to have a moderating effect for the daytime model, but was not significant at the $p = 0.05$ level. Standard deviation of speed appeared to be positively correlated to the number of crashes in the nighttime model, but again, was not significant at the $p = 0.05$ level. Roads with the highest quality of conditions (wide shoulders, fewer curves and grades, and absence of junctions) were associated with high speeds but low numbers of crashes and roads with the lowest quality of conditions were associated with low speeds and higher numbers of crashes, demonstrating the need to consider road conditions when evaluating a speed-crash relationship.

Elvik et al. (2019) conducted a meta-analysis of 49 previous studies from several countries published since 2000 on the relationship between speed and road safety where an intervention was made to influence speed through either a change in speed limit or a change in enforcement, particularly by automated speed cameras. Despite improvements in vehicle technology the relationship between speed and crashes remain strong. The speed limits before an intervention ranged from 50 to 110 km/h (30 to 68 mph). Speed limits post intervention ranged from 40 to 110 km/h (25 to 68 mph). The results of the meta-analysis provided support for both the power model and the exponential model. Both of these models have been proposed to model a relationship between speed and the number of injury or fatal crashes. *(Nilsson, 2004; Elvik, 2013)*.

Caviedes & Figliozzi (2017) investigated potential risk factors contributing to fatal and severe crashes involving pedestrians and bicyclists on Oregon state roads with speed limits ranging from approximately 20 to 65 mph. Crash data from 2007 to 2014 was collected from the Oregon Statewide Crash Database and a total of 1,649 pedestrian and 1,214 bicyclist crashes were analyzed. The findings suggested that posted speed limit was a significant variable in predicting severe and fatal pedestrian crashes with a posted speed limit of 50 mph or greater being associated with a 2.3% increase in severe or fatal crash risk. The study did not find posted speed limit to be a significant risk factor for bicyclist crashes, but the authors noted that the vast majority of bicyclist crashes studied occurred on roads with posted speed limits between 35 and 50 mph and this reduced variability may have affected the results.

Figliozzi et al. (2018) performed an analysis of urban and rural intersection vehicle-pedestrian crash data from 2007 to 2014 on Oregon state roads. Vehicle exposure was controlled by considering the length of the highway network or VMT (using pedestrian crashes per 10,000 AADT and highway length). Results indicated when controlling for the length of the highway network, the crash frequency increased as AADT increased up to 30,000 with the highest frequency between 15,000 and 30,000 AADT. When controlling for VMT, a similar trend of increasing crash frequency with increasing AADT was found. Both measures of exposure showed the highest crash frequency for urban intersections occurred with 35-50 mph posted speed limits. Crash frequency also tended to increase with increasing road width or increasing number of lanes for both exposure measures.

3.1.1 Network Effects

A meta-analysis of sample of regression studies in the US focused on rural interstates where speed limits were increased and also took a statewide approach counting fatalities on all roads in the network. Results show that count fatalities increased more on rural interstates that on all roads in the network; however, statewide fatality rates per VMT decreased *(Castillo-Manzano, et al., 2019)*. The authors hypothesize that these results can be attributed to the "diversion effect" or traffic switching to roads with a higher speed limit, i.e. there is an overall statewide reduction because crash rates per VMT are significantly lower on freeways. However, it was not possible able to test this hypotheses due to the lack of suitable data (for roads where speed limits were not raised) from primary studies. The diversion effect has been documented by many studies starting in the 1990's such as Wagenaar et al. *(1990)* and Rock *(1995)*.

Another effect that takes place at the network level is the "speed spillover effect". In this case it is hypothesized that drivers get used to driving at higher speeds; after leaving roads where the maximum speed limit has changed, drivers operate at a higher speed on roads where the speed limit has not changed. Many studies starting in the 1990's such as Brown et al. *(1990)* and Garber and Graham *(1990)* have documented the speed spillover effect.

3.1.2 Power Model in Urban Areas

Nilsson proposed power relationships connecting changes in traffic speeds with changes in road crashes at various levels of injury severity, for example, increases in fatal crashes are related to the 4th power of the increase in mean speed, increases in serious casualty crashes (those involving death or serious injury) according to the 3rd power, and increases in casualty crashes (those involving death or any injury) according to the 2nd power *(OECD, 2006)*. These relationships were empirically derived based on speed changes resulting from a large number of rural speed limit changes in Sweden during 1967-1972 but later meta-analysis confirmed the power relationship.

Nilsson's power model seems reasonable for rural highways and freeways but the model does not appear to be directly applicable to traffic speed changes on urban arterial roads *(Cameron & Elvik, 2010)*. The estimated power, connecting speed and serious injuries, is 1.57 on urban arterials and significantly less than the 2.59 and 4.93 power values for rural highways and freeways. Perhaps the mean speed is not sufficient to represent the influence of speed on serious injuries in urban environments; perhaps the mean should be supplemented by a measure of the distribution of speeds or other influential variables such as exposure. Cameron & Elvik *(2010)* conclude that there is a critical need of additional research to further study the safety relationships relating urban traffic and crashes.

3.1.3 Speed and Crash Frequency Inconsistencies

The National Transportation Safety Board (NTSB) notes there exists a complex relationship between speed and crash involvement *(NTSB, 2017)* and therefore it is not surprising to find some inconsistencies in some research results that can be the result of different estimation approaches, data quality, and/or missing data.

Conclusions reached by *Islam & El-Basyouny (2015), Gargoum & El-Basyouny (2016), Taylor et al. (2000), Wang et al. (2018), and Gitelman et al. (2017b)* are generally consistent for average speed and crash frequency. However, some inconsistencies were found in the relationship between crash frequency and the standard deviation of average speeds. *Gargoum & El-Basyouny (2016)* found crash frequency and the standard deviation of average speed (a measure of speed variation) to be negatively correlated (though only statistically significant at the 10% significance level) and *Gitleman et al. (2017)* found inconsistent correlations with standard deviation that were not statistically significant. IN contrast, *Taylor et al. (2000)* and *Wang et al. (2018)* found them to be significantly positively correlated.

Traffic flow, road geometry, road type, land use, driver characteristics, and different research methodologies may all contribute to the inconsistent relationship between speed and crash involvement *(NTSB, 2017)*. When it comes to crash frequency and road type in urban areas, local roads account for 22% of fatal crashes involving speeding vehicles while only accounting for 15% of all urban VMT, suggesting crash risk attributed to speeding varies depending on road type and function *(NTSB, 2017)*. It should be noted that pedestrians and cyclists accounted for 3.9% of all the fatalities, including all types of roads *(NTSB, 2017)*.

Inconsistencies can also be found due to use of different exposure metrics as shown by *Pei et al. (2012).* Traffic flow, speed, road design, weather condition, and temporal distribution data was gathered for roadway segments in Hong Kong. Crash data was sourced from the Traffic Information Center. The authors found the rate of crash involvement decreased as speed increased when using distance-based exposure measures (such as crashes per vehicle mile traveled, VMT), but when using time-based exposure measures (such as vehicle hours traveled), the crash involvement rate increased with increased speeds.

3.2 SPEED AND CRASH SEVERITY

This subsection reviews crash severity by user type.

3.2.1 Crash Severity - Vulnerable Users

In a literature review prepared for the USDOT *(Leaf & Preusser, 1999)*, a review of empirical data associated to vehicle-pedestrian crashes estimates that a pedestrian has a 10% likelihood of severe injury or fatality if struck by a vehicle moving at 20 mph and up to an 80% likelihood if the vehicle is moving at 40 mph. Data used in the analysis was collected from the State of Florida, the Fatality Analysis Reporting System (FARS), and the National Automotive Sampling System's (NASS) General Estimates System (GES) database which consists of a nationally representative sample of police reported motor vehicle crashes of all types.

The Minnesota Department of Transportation (MnDOT) reviewed five years of pedestrian-involved crash data from Minnesota, Iowa, and Wisconsin in relation to consideration of reducing the default urban speed limit from 30 to 25 mph. Iowa and Wisconsin have 25 mph speed limits for residential roadways. Pedestrian injury rates and fatality rates were calculated on a number of exposure measures including per million residents, per 100 square miles, per million licensed drivers, per million registered vehicles, and per billion vehicle miles traveled (VMT). For all measures of exposure for both injuries and fatalities, rates in Iowa were the lowest, with Minnesota's slightly higher and Wisconsin's the highest, yielding inconclusive results on the potential safety benefits of a 25 mph speed limit *(MnDOT, 2008)*. It must be noted that this study did not account for pedestrian exposure.

Rosén & Sander (2009) derived a function to predict adult pedestrian fatality risk based on crash data from a previous German study conducted between 1999 and 2007. A total of 353 cases divided into three injury severity categories were used to derive the function. The categories were weighted to be representative of national statistics on pedestrian crashes. The resulting function indicated the risk of a fatality rapidly increases at impact speeds of 60 km/h (37 mph) and above.

Richards (2010) calculated the pedestrian fatality risk versus impact speed using a logistic regression method on two United Kingdom data sources (the On the Spot project and police fatal files) and then applied the same method to a dataset from the 1970s and to the dataset used by *Rosén & Sander (2009)*. All datasets were weighted to be representative of the national statistics in terms of severity level. Comparing the risk of fatality from the different datasets showed the risk was higher in the 1970s. Overall, the risk of pedestrian fatality was low up to impact speeds of 30 mph and then increased rapidly– between 3.5 and 5.5 times from 30 mph to 40 mph.

Using data from the NASS's Pedestrian Crash Data Study, the risk of severe injury or fatality by a pedestrian struck by a forward-moving car, pickup, truck, van, or SUV was estimated in relation to vehicle impact speed *(Tefft, 2013)*. A total of 315 records were analyzed using a 95% confidence interval. Results showed the average risk of severe injury was 10% at a speed of 17.1 mph, 25% at 24.9 mph, 50% at 33.0 mph, 75% at 40.8 mph, and 90% at 48.1 mph. The average risk of fatality was 10% at an impact speed of 24.1 mph, 25% at 32.5 mph, 50% at 40.6 mph, 75% at 48.0 mph, and 90% at 54.6 mph.

Kröyer (2015a) investigated the relationship between mean travel speed and injury severity or risk of fatality for a struck pedestrian as mean speeds are probabilistically related to individual travel speeds at crash locations. Records of injury crashes where a pedestrian was struck by a motorized vehicle (excluding motorbikes) from 2004 to 2008 were obtained from the Swedish Traffic Accident Data Acquisition (STRADA) database. Crash locations from the original dataset were drawn at random and the corresponding crashes created a second dataset. Proportions of crashes within each injury severity group (minor, severe, fatal) were weighted to match the population proportions. Spot speed measurements were taken at all locations in dataset two to determine mean free flow speeds. Results of the analysis indicated minor injury crashes occurred at locations with mean speeds up to 55 km/h (35 mph) and that there was no statistically significant difference in mean speeds for locations where severe injuries occurred ($p = 0.114$). Mean speeds at locations where fatal injuries occurred were significantly higher than locations of minor injuries ($p = 0.003$) and from locations of severe injuries ($p = 0.031$). Approximately 63% of fatal crashes in this study occurred at sites with mean travel speeds between 40 and 50 km/h (25-31 mph). Age was also found to correlate with fatality risk with ages 0-15 and 65+ associated with higher risk. *Kröyer* states that caution should be taken when applying these results as exposure and speed may both affect crash and injury risk.

To further the study of exposure and crash risk between pedestrians or bicyclists and motorized vehicles at urban intersections, *Kröyer (2015b)* obtained crash data from 2008 to 2012 from STRADA for six mid-sized Swedish cities. Speed limit (which ranged from 30 to 70 km/h [20 to 45 mph]), road classification, type of traffic control, sight conditions, and level of bicycle integration with motor vehicle traffic were recorded for each site. Results revealed a non-linear correlation suggesting that the number of crashes between pedestrians or bicyclists and motorized vehicles does not increase proportionally with the increase of the exposure of pedestrians, bicyclists, and/or motorized vehicles. None of the geometric variables were found to be significant. The author noted several theories to explain the 'safety in numbers' effect. Higher numbers of pedestrians and bicyclists may influence drivers' awareness and expectations, or higher volumes of motor vehicles may increase awareness among pedestrians and bicyclists. More experience in traveling as a particular type of road user may lead to an acquisition of skills resulting in lower crash risk. The converse of 'safety in numbers' (i.e. numbers in safety) may be also true since road users may be more likely to choose routes that are safer. Additionally, higher exposure of road users may correlate with better infrastructure and maintenance.

Caviedes & Figliozzi (2017) investigated potential risk factors contributing to fatal and severe crashes involving pedestrians and bicyclists on Oregon state roads with speed limits ranging from approximately 20 to 65 mph. Crash data from 2007 to 2014 was collected from the Oregon Statewide Crash Database and a total of 1,649 pedestrian and 1,214 bicyclist crashes were analyzed. The findings suggested that posted speed limit was a significant variable in predicting severe and fatal pedestrian crashes with a posted speed limit of 50 mph or greater being associated with a 2.3% increase in severe or fatal crash risk. The study did not find posted speed limit to be a significant risk factor for bicyclist crashes, but the authors noted that the vast majority of bicyclist crashes studied occurred on roads with posted speed limits between 35 and 50 mph and this reduced variability may have affected the results.

Bicycle crash data involving motor-vehicles was collected from the New Jersey Department of Transportation between the years of 1997 to 2000 in order to develop a bicycle route safety rating model based on injury severity *(Allen-Munley et al., 2004)*. Posted speed limit (mean of all locations was 25.5 mph), lane width, and motor vehicle volume per lane were among the selected explanatory variables to investigate. The model did not demonstrate a clear relationship between posted speed limit and injury severity, but it was noted that actual operating speeds can vary greatly from the posted speed limit. The model did find significant injury severity relationships for both lane width and volume per lane with wider lanes and lower volumes increasing injury severity. Possible explanations offered that wider lanes and lower volumes can both be associated with higher operating speeds.

Eluru et al. (2008) obtained data from the 2004 General Estimates System (GES) including 1223 records involving pedestrians and 1721 involving bicyclists to develop a model regarding selected explanatory variables and non-motorist injury severity. Posted speed limit was divided into three categories – less than 25 mph, 25 to 50 mph, and greater than 50 mph. Posted speed limit was found to be a significant variable in the model with increasing posted speed limits associated with higher severity of injuries.

Wang and Kockelman (2013) analyzed the relationship between 3-year pedestrian crash counts in Austin, Texas, metropolitan area. Results suggest that greater mixing of residences and commercial land uses is associated with higher pedestrian crash risk across different severity levels. This is likely explained by the fact that mix land uses produces more conflicts between pedestrian and vehicle movements. Transit service and arterial network density are associated to higher severe-crash rates and sidewalk provision and local network density are associated with lower severe-crash rates. An exposure measure for pedestrian crashes, pedestrian VMT, is utilized in the analysis. A model of pedestrian VMT is estimated using Austin's travel survey data set and variables such as area size, population, sidewalk length, and local streets length per each geographical unit.

3.2.2 Crash Severity for non-Vulnerable Users

Data sampled from the GES database in 2014 indicated the estimated percentage of serious injuries or fatalities for non-pedestrian single vehicle crashes increased with higher vehicle speeds when the vehicle was reported as speeding *(NTSB, 2017)*.

Richards (2010) used data from the On the Spot project and from the Co-operative Crash Injury Study to look at the relationship between the change in velocity (delta-v) and driver injury severity. Again, the data were weighted to match the proportion of casualties occurring nationally and logistic regression was applied. For frontal impacts, the fatality risk was approximately 3% for a delta-v of 30 mph, 17% for 40 mph, and 60% for 50 mph. The risk of fatality in a side impact was higher than for a frontal impact with an approximate risk of 25% for a delta-v of 30 mph, and approximately 85% for a delta-v of 40 mph.

Jurewicz et al. (2016) re-evaluated models previously developed by *Bahouth et al. (2014)* to generate a generalized relationship between vehicle impact speed, vehicle impact angle, and severe injury probability (Abbreviated Injury Scale of 3 or higher, where 6 is the maximum). The data from *Bahouth et al. (2014)* was weighted to match the distribution of severity and type of crashes occurring across the U.S. and was limited to vehicles of year 2002 or newer. The models controlled for seatbelt use, rollover or secondary impacts, and occupant age. *Jurewicz et al. (2016)* used the assumptions that vehicle masses were normally distributed and that collisions were inelastic in the analysis, but noted the second assumption may lead to a more conservative critical impact speed in side collisions. Critical impact speeds were defined at the 10% risk of severe injury for each crash type. Head-on and side collision critical impact speeds were approximately 30 km/h (20 mph) and rear-end critical impact speed was approximately 55 km/h (35 mph). For vehicle-pedestrian crashes, an alternate empirical relationship based on data from the 1960s and 70s was chosen to determine the critical impact speed which was found to be approximately 20 km/h (12 mph).

Vorko-Jović et al. (2006) studied factors that increased the risk of involvement in an urban road traffic accident using the linked hospital and police reports sourced from Ministry of Interior's Road Traffic Accident Surveillance for the Republic of Croatia. When exceeding the speed limit was listed as a factor, the odds of a fatal outcome was 2.56 times the odds of a non-fatal outcome ($p = 0.0012$) and the odds of a fatal or severe injury outcome was 1.47 times the odds of a minor injury outcome ($p = 0.04$).

Penmetsa & Pulugurtha (2016) collected crash data from the Highway Safety Information System for the state of North Carolina from 2010 through 2013 to examine the risk drivers pose to themselves by violating traffic rules, and the risk these violation-committing drivers pose to other drivers who did not violate any traffic rules. Odds ratios were calculated for a number of traffic violations listed as the primary contributing factor of the crash and a 95% confidence interval was used. The reference variable was defined as the risk drivers pose by disregarding a traffic signal. The results showed that the traffic violation with the highest odds of the driver being severely (including fatally) injured was 'exceeding the speed limit' at 39.42 times the odds of being severely injured by disregarding a traffic signal. A driver 'exceeding the speed limit' also increased the odds of a non-violation-committing driver being severely injured by 6.409 times and was the second highest odds-increasing violation in regard to the risk posed to other drivers.

3.3 SUMMARY

Many studies all over the world have focused on the effect of impact speed or proxies like posted speed limit on crash frequency and crash severity. Most of the results are consistent and indicate that the risk of severe injury and fatality increases rapidly, non-linearly, with speed. However, Nilsson's power model that is reasonable for rural highways and freeways but the model does not appear to be directly applicable to traffic speed changes on urban arterial roads.

The laws of physics dictate that crash severity increases with an increase in collision speed and vulnerable road users are particularly at risk due to their lack of protection *(NTSB, 2017)*. As expected, the crash severity for active users increases even faster as a function of impact speed. Few studies focus on the relationship between speed changes and crashes in urban areas. The number of studies is even fewer if the focus is on speed limits in urban areas with a high percentage of active users. In most studies there are no variables that account for pedestrian and cyclist exposure.

The NCHRP Project 20-05, *Pedestrian Safety Relative to Traffic Speed Management (Sanders et al., 2019)* presents a literature review exploring how speed is related to pedestrian injury severity and describes a range of effective countermeasures to reduce speed. This report indicates that there are several research gaps such as a better understanding of the effects of traffic speed management in relations to pedestrian safety, evaluation of comprehensive programs such as vision zero, and a better evaluation of the long-term effects of spillover effects and traffic diversions.

4.0 DRIVER COMPLIANCE OF SPEED LIMIITS

Speeding can be defined as either exceeding the legal limit or as driving too fast for the prevailing conditions. The Organisation for Economic Co-operation and Development (OECD) identifies speeding as a serious societal and public health issue throughout the world *(OECD, 2006)* and the World Health Organization (WHO) states, "excessive or inappropriate speed is the most important factor contributing to the road injury problem faced by many countries," *(Global Road Safety Partnership, 2008)*.

Reducing the speed limit alone has been shown to produce little effect on average driving speed. The ratio of the change in driving speed to the change in speed limit is approximately 1:4 *(OECD, 2006)*. Therefore, increasing compliance when speed limits are reduced has been the subject of several research studies.

4.1 CURRENT LEVELS OF COMPLIANCE

Between 2005 and 2014, law enforcement officers cited speed as a contributing factor in 31% of all traffic fatalities in the United States *(NTSB, 2017)* and between 2015 and 2016, the number of speeding related fatalities increased by 4% *(AAA, 2018)*.

Based on an online survey administered throughout the U.S. in late 2017 *(AAA, 2018)*, the AAA Foundation for Traffic Safety found that 88.2% of drivers view speeding on residential streets as a somewhat or very serious threat to their personal safety and that social disapproval of driving 10 mph over the speed limit on a residential street is high (only 14% of respondents rated the behavior as completely or somewhat acceptable). Despite these views, nearly half of respondents (47.6%) reported driving 10 mph over the speed limit on a residential street at least once in the past 30 days with 12.9% indicating they engaged in the behavior fairly often or regularly.

Exceeding the speed limit has also been an issue within countries of the European Union where speeding is occurring more frequently and especially on lower speed urban roads *(Kallberg et al., 1999)*.

4.2 SPEED LIMIT CREDIBILITY

When an online survey was administered throughout four states in Australia to study the attitudes toward lowered speed limits on rural and urban roads, support for lowered speed limits on urban roads was poor with about 70% responding the proposed reduced limit was inappropriately low. The research also sought to gain a greater understanding of the reasons why a motorist might choose to exceed the speed limit and the characteristics of these motorists in order to improve adherence to speed limits through potential targeted interventions. *(Lahausse et al. 2010).*

Dinh & Kubota (2013a) wanted to explore possible reasons for drivers exceeding the speed limit by employing the theory of planned behavior as a frame of reference. A vehicle spot speed survey and a questionnaire survey were conducted together on two 30 km/h (20 mph) residential streets in Japan. Speeding behavior was significantly influenced by speeding intention and perceived appropriateness of the speed limit was found to be highly correlated with the intent to speed. With 37% of questionnaire respondents claiming a 30 km/h (20 mph) limit was too slow, the authors implied drivers may be more compliant if the low speeds were regarded as more reasonable.

Lee et al. (2017) was interested in the factors used by drivers to determine speed limit credibility levels. The study was composed of two experiments involving two groups of participants judging appropriate speed limits of 35 different road segments in Malaysia which were represented by photos captured from a driver's point of view.

- In the first experiment, the posted speed limits were erased from the photos and 29 Malaysian drivers were asked to indicate the driving speed they thought was appropriate. Results from this first experiment revealed incongruity between the speeds the participants chose and the actual speed limits of the roads in the photos. Participants chose significantly higher speeds for roads which had speed limits ranging from 40-80 km/h (25-50 mph) and chose significantly lower speeds for roads with speed limits of 110 km/h (70 mph). No significant difference was found for the 90 km/h (55 mph) speed limit roads. Analysis of these results suggested road width, horizontal alignment, sight distance, the presence of lighting poles, the presence of intersections, and the number of lanes all appeared to significantly influence drivers' speed choice.

- In the second experiment of the study, the same 35 photos were edited to show speed limits calculated as 10% higher, 10% lower, 50% higher, or 50% lower than the speeds chosen by participants in the first experiment. These edited photos were shown to a different group of participants comprised of 109 Malaysian drivers who were asked to indicate the driving speed they thought was appropriate. The difference between the drivers' indicated appropriate speeds and the speed limits shown in the edited photos was calculated. Participants judged appropriate driving speeds to be significantly lower than the speed limits displayed in the photos of the 10% and 50% higher categories. The judged appropriate speeds were significantly higher for photos displaying speed limits in the 50% lower category. Finally, the speed limits shown in the 10% lower category photos were found to be mostly in accordance with what the drivers deemed appropriate which suggested to the researchers that drivers found those speed limits more credible.

4.3 SELF EXPLAINING ROADS

The concept of self-explaining roads (SER) is to utilize visual cues or visual characteristics of roads to influence driver behavior and speed selection. *Charlton et al. (2010)* report the results of a SER design change in an urban area. The study area was divided into a control area and a treatment area with SER treatments designed to maximize visual differences. Local roads received treatments such as increased landscaping, community islands, and removal of road markings. Collector roads received increased delineation, cycle lanes, and pedestrian treatments. Figure 4.1 shows the before and after speed data. Three months after implementation there was a significant reduction of speeds on local roads and increased homogeneity of speeds on both local and collector roads.

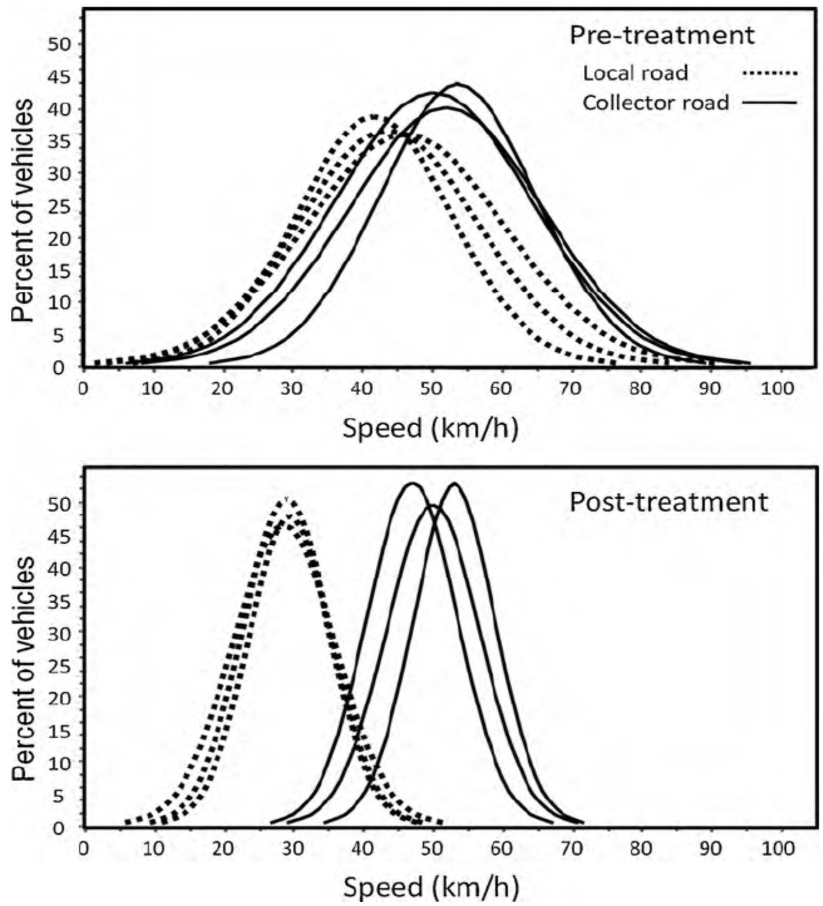

Figure 4.1: Distribution of speeds before and after SER treatments (Reproduced from Charlton et al., 2010).

Charlton & Starkey (2017) were interested in how drivers choose the "correct" speed. Using a driving simulator, 55 drivers were asked to drive a video of a variety of urban roads. The drivers were then asked to sort photos of the previously driven roads into categories of similar driving behavior, and then to answer a series of questions about their views regarding speeds and difficulty of operation on those roads. Participants tended to categorize road photos based on visual characteristics of the roads and roadsides. These self-explaining or self-determined road categories took precedence in speed choice over prior experience in the simulator, even when the posted speed limit was visible in many of the video clips, indicating drivers may rely on their own default values to develop expectations of a "correct" speed instead of relying on the posted speed limit.

4.4 SOCIAL INFLUENCE AND COMPLIANCE

A qualitative study in Great Britain was conducted to examine potential roles of social marketing on compliance *(Toy et al. 2014)*. The study concluded that the most promising method to create permanent change is by making compliance of the 20 mph limit the new social norm through the use of well-crafted campaigns.

Even if drivers are swayed to support lower speed limits, *Tapp et al. (2015)* discovered the link between support and compliance is not as clear as it seems. Again in Great Britain, an online questionnaire was administered to determine levels of support and intended compliance of a new, lower 20 mph speed limit and found that 17% of respondents claimed they might not comply despite being in support of it. The research looked into reasons why drivers may not comply and found self-enhancement bias (the belief they are 'better than average' drivers), social contagion (adopting speeds according to comparisons with other drivers on the road), and inattentive or automatic driving behavior were the predominant categories of reasons for non-compliance.

Tapp et al. (2016) took a deeper look into previous research *(Toy et al. 2014, Tapp et al. 2015)* to see how the vulnerable "mainstream middle," i.e., those who are supportive but may not comply and those who indicate they may comply although not in support, are susceptible to behavioral change due to social contagion and driving automaticity (lack of active concentration on the driving task). Word of mouth campaigns emphasizing messages of "fewer serious accidents," that "children can play safely," and that "streets would be more pleasant to live in" were indicated as a possible method to induce 20 mph as the new norm, although the authors noted an increased level of police enforcement would likely be required to facilitate the shift toward compliance.

In addition to the motivational elements explained through the theory of planned behavior *(Dinh & Kubota, 2013b)*, *Kallberg et al. (1999)* mentions that speeding behavior is driven by external feedback from elements such as road design and behavior of other road users.

4.5 EXPECTED ENFORCEMENT

A study focusing on driver perceptions and compliance was conducted utilizing data from a survey of 988 drivers in Indiana *(Mannering, 2009)*. The results show a link between the speed that is perceived as safe by the drivers and the speed that is utilized for enforcement, i.e. drivers' perception of a safe speed is strongly linked to the speed above the speed limit at which drivers think they will receive a speeding ticket. For example, a 1% increase in the perceived probability of receiving a speeding ticket results in a 1.97% reduction in drivers' probability of thinking that an unsafe speed is 5 mph above the speed limit. In addition, the perception of a safe speed level was influenced by age, gender, speeding record, and drivers' ethnicity.

4.6 SUMMARY

Overall, there have been a limited number of studies on factors affecting speed limit compliance. A survey based analysis indicated public opinion in the US was negative towards speeding on residential streets. Similarly, respondents to a survey in Great Britain were supportive of reducing speed limits. However, a significant proportion of the US and UK respondents admitted to engaging in speeding behavior and having intentions of not complying, respectively. In comparison to Great Britain's support for lower speed limits, a majority of respondents from a survey in Australia were against lowering speed limits in urban areas.

Studies indicate that drivers choose their speeds according to their own perception of what is reasonable based on their self-determined road categories and that simply changing a speed limit sign may not be an effective way to change drivers' perceptions. Self-explaining roads and reasonable speed limits are likely to reduce speeding. Road design elements such as road width, horizontal alignment, and sight distance, the presence of lighting poles, the presence of intersections, and the number of lanes all appeared to significantly influence drivers' speed choice.

Marketing campaigns and enforcement are important elements to help shift personal beliefs and social norms toward promoting a culture of compliance.

5.0 SPEED MANAGEMENT PRACTICES

Kallberg et al. *(1999)* considers speed management to cover all actions that promote the adoption of driving speeds that are acceptable or desirable from society's point of view. A holistic speed management program is a strategy to address concerns of unlawful or undesirable speeds at a specific location, along a corridor, or within a jurisdiction's road network. The program should include elements of engineering, enforcement, education, and emergency services *(Bagdade et al., 2012)*.

Effective speed management programs require an understanding of the extent, nature, and underlying factors of the speed problem. It is especially important to take into account the presence of pedestrians, bicyclists, and other vulnerable road users *(Global Road Safety Partnership, 2008)*.

Speeding issues should be identified by analyzing archived traffic data, reviewing crash data while considering exposure elements such as crashes per million VMT or crashes by traffic volume; conducting site reviews to look for skid marks, ruts on the outside of curves, worn centerline markings, and damage to signs or guardrails from vehicles; reviewing speeding citation records; and consideration of public input. Partner agencies should be identified and specific goals related to the identified speeding issues should be set. Countermeasures that may address the problem should be selected and then implemented systematically. Finally, the countermeasures implemented should be evaluated to determine the progress being made toward the previously established goals *(Bagdade et al., 2012)*.

5.1 HISTORY OF SPEED MANAGEMENT

OECD (2006) indicates that some types of speed management practices have been used since the late 1920s in the US mainly to reduce traffic volumes in urban/local streets. In the 1960s, Sweden promoted the development of residential areas which were accessed by a system of ring roads. Near the same time, the concept of the "Woonerf," or a "living street," appeared in the Netherlands. Speed management in urban areas has increased in popularity throughout the world since.

The concept of a self-explaining road came about in the 1960s and 1970s and was further developed in the 1980s as a way to assist drivers in choosing an appropriate speed by using homogeneous and consistent design principals to reduce variability in current road infrastructure.

5.2 TRAFFIC CALMING

The *U.S. Traffic Calming Manual (Ewing & Brown, 2017)* indicates that "Traffic calming involves changes in street alignment, installation of barriers and other physical measures to reduce traffic speeds and/or cut-through volumes, in the interest of street safety, livability, and other public purposes." In addition to helping achieve greater compliance with speed limits, traffic calming may help decrease injury severity in traffic crashes and help achieve greater balance among transportation modes by encouraging walking, bicycling, and street life *(FHWA, 2013.; Ewing & Institute of Transportation Engineers, 1999)*. Traffic calming projects should also include community awareness and education components *(South Carolina Department of Transportation, 2006)*.

5.2.1 Street Eligibility Criteria

A survey of 20 leading jurisdictions in traffic calming was performed in 2004. Approximately half of these jurisdictions limited eligibility to residential streets. Some of the jurisdictions limited eligibility to local streets while others extended it to collector streets. Six of the jurisdictions (including Portland, OR) considered the eligibility of arterials on an exception basis with limited options of applicable measures. The median qualifying 85^{th} percentile speed was nine mph over the posted speed limit and the qualifying average daily volume was higher than 1200 vehicles per day; in some cases there is a maximum volume warrant *(Ewing & Brown, 2017)*.

According to *Bagdade et al. (2012),* traffic calming countermeasures tend to be applied to roads with speed limits of 30 mph or less.

5.2.2 Traffic Calming Toolbox

Traffic calming includes non-physical as well as physical measures. Non-physical methods include:

- Psycho-perceptive measures such as edge or centerline striping and optical speed bars.
- Regulatory measures such as stop signs and turn restrictions. These require enforcement to be most effective *(Ewing & Brown, 2009)*.
- Signal timing for progression. This method may be effective on streets with short blocks and short cycles and several signalized intersections *(Ewing & Brown, 2009)*.

Physical methods include:

- Volume control measures such as full or partial street closures and median barriers to prevent through movement at a cross street.
    - Full street closures are widely discouraged among cities as they are generally seen as too restrictive *(Ewing & Institute of Transportation Engineers, 1999)*.
    - Volume impacts are more complex as they depend on the entire surrounding street network and analysis should be performed to determine the effects on the network from the redistributed traffic *(Ewing & Brown, 2009)*.
- Vertical measures such as speed bumps, humps, lumps, and tables or raised intersections and crosswalks.

- Speed humps and lumps were found to have the most significant impact on 85th percentile speeds, reducing them by an average of 20% *(Ewing & Brown, 2009)*.

- Speed humps are not recommended for emergency routes due to the delay they may cause emergency responder vehicles *(Colman, 1997)*.

- Speed tables are a longer version of speed humps, typically 22 feet in length with a flat section on top *(Ewing & Brown, 2009)*.

- Speed lumps (also known as speed cushions) are speed humps with wheel cutouts to allow larger vehicles to pass unaffected *(National Association of City Transportation Officials [NACTO], 2013)* and were developed to be more emergency vehicle friendly.

- Horizontal diversion measures such as traffic circles, roundabouts, lateral shifts, and chicanes or serpentine curves.

- Reduction of the street area by the addition of curb extensions, medians, and pinch points.

    - Pinch points can present safety issues for bicyclists by being squeezed or cut off by vehicles trying to pass *(FHWA, 2013)*.

Costs associated with implementing the measure, landscaping maintenance needs, and snow removal needs should also be considered when choosing appropriate measures. *(Ewing & Institute of Transportation Engineers, 1999; Ewing & Brown, 2017; FHWA, 2013; South Carolina Department of Transportation, 2006.)*

5.2.3 Safety Impacts of Traffic Calming

Reducing vehicle speeds and eliminating conflicting movements may result in fewer collisions or reduced injury severity. After adjusting for changes in traffic volumes, Ewing & Brown *(2017)* stated that all traffic calming measures reduced the average number of collisions and that 22-foot speed tables and traffic circles produced results that were statistically significant for p = 0.05.

Ponnaluri & Groce *(2005)* evaluated the effectiveness of 12-foot speed humps on traffic volume and vehicle speeds in a pre and post installation study. Traffic volume and speed data were collected pre and post-installation via pneumatic tubes in 15-minute intervals over a consecutive 48-hour typical weekday period at three locations along a section of road with a posted speed limit of 25 mph. A total of five 3.5 inch high, 12 feet wide speed humps were installed along the section of road spaced 405-635 feet apart. Traffic volume dropped by 5-29%, and 85th percentile speeds decreased 8-29% over the three locations after installation. The smallest reductions in volume and 85th percentile speed occurred at the same location, and the authors attributed the smaller amount of change compared to the other two sites to having more recent pre-installation data and lower pre-installation 85th percentile speed at that location.

Gitelman et al. *(2017a)* observed road user behavior before and after raised crosswalk and preceding circular speed hump combinations were installed on urban arterial and collector roads at non-signalized, mid-block locations in Israel. Mean speeds before installations ranged from 31 to 58 km/h (20 to 36 mph). Eight sites with two crosswalks each were chosen. Five of the locations had 15 cm high (6 in.) trapezoidal humps (raised crosswalks) combined with 8-10 cm high (3-4 in.) circular humps. The remaining locations had 10-12 cm high (4-5 in.) trapezoidal humps with 6-8 cm high (2-3 in.) circular humps. Speed measurements of 100 free-flow vehicles were performed with a laser speed gun at each of the 16 crosswalks in the study. Other road user behavior was recorded on video for six hours including three during daytime and three during evening. Results indicated vehicle travel speeds decreased significantly at the majority of the sites with larger and sustained decreases at locations with higher speed humps. An increase in the number of vehicles yielding to pedestrians in the near lane and the far lane was observed at six and seven of the crosswalks, respectively. A decrease in vehicle-pedestrian conflicts was observed at five crosswalks while at other sites either no significant difference was found or no conflicts were observed before or after the installation. The percentage of pedestrians crossing fully within the designated area increased at the majority of sites. Mixed changes were observed in regard to pedestrians following safe crossing rules. The percentage of pedestrians who stopped before crossing decreased at nine crosswalks, increased at three, and did not change at four crosswalks. The percentage of pedestrians who checked traffic before crossing decreased at two crosswalks, increased at seven, and did not change at the remaining seven.

Chen et al. (2013) studied the effects of thirteen safety countermeasures used in New York City including seven intersection-based measures and six segment-based measures on the average crash rate per year per location. Twenty years of crash data were obtained from police and driver reports held by the New York State Department of Motor Vehicles. Countermeasures were evaluated based on the calculated crash modification factors (the expected ratio between actual crashes at treated locations and expected crashes at those locations had there been no treatment) and their standard errors. Since the average number of crashes in the before period of the treatment group was higher than the number of crashes in the untreated comparison group for most of the countermeasures, the crash modification factors were adjusted based on an analysis of covariance. Results of the adjusted crash modification factors showed:

- An all-pedestrian signal phase, increasing the pedestrian crossing time, or adding a high visibility crosswalk significantly reduced the expected number of vehicle-pedestrian crashes;

- Installation of traffic signals or adding a left-turn phase significantly reduced crashes of all types;

- Lowering the posted speed limit or installation of speed humps were found to have a limited impact on crashes (not significant at the 95% confidence level);

- A road diet countermeasure (reducing the number of motor vehicle travel lanes) was found to significantly reduce crashes of all types while the addition of bus lanes was found to significantly increase the number of crashes of all types.

- Addition of bicycle lanes was also found to significantly increase the number of crashes at intersections. However, the authors note they were unable to control for possible bicyclist volume increases between the before and after periods and that the bicycle lanes in this study typically did not include any intersection treatments *(Chen et al., 2013)*.

Although traffic calming has the potential to reduce vehicle speeds, increase speed limit compliance, and reduce collisions, implementation of such measures has often been met with opposition by fire departments over concerns of added delay to emergency response times. In response, some cities have chosen to directly involve the fire department in the approval process while others have designated primary emergency response routes and deemed them ineligible for traffic calming or limited available measures on those routes to emergency vehicle friendly measures *(Ewing & Brown, 2017)*.

5.3 TRAFFIC CONTROL AND REGULATORY COUNTERMEASURES

While speed limits are the most common method for managing speed *(NHTSA, 2014)*, studies have indicated that speed limits alone are usually not sufficient for effectively controlling operating speeds *(NTSB, 2017; AAA, 2018; Kallberg et al., 1999)*.

Traffic control devices such as the installation of advisory speed signs, speed activated or speed feedback signs, pavement speed limit or "SLOW" markings, and psycho-perceptive measures such as optical speed bars can be a cost-effective method to reduce speeding. Speed advisory signs installed ahead of a curve have been found to reduce speeds by 2-3 mph and are associated with a crash modification factor (CMF) of 0.71-0.87 *(Bagdade et al., 2012)*. Advisory signs should be consistent in their application and advice in order to establish consistent driver expectations *(Global Road Safety Partnership, 2008)*. Speed activated or speed feedback signs may be effective at reducing speeds in transition areas but may lose effectiveness if used too frequently. Speed activated or speed feedback signs have been associated with a reduction in speed of 2-10 mph and a CMF of 0.54 *(Bagdade et al., 2012)*.

Optical speed bars are transverse pavement markings with decreasing spacing in the direction of travel, causing drivers to perceive they are traveling faster than their true speed. Optical speed bars may reduce speeds by an average of 2 mph according to *Bagdade et al. (2012)*.

Although psycho-perceptive measures can be relatively low cost, these methods are generally not effective on their own and can be more effective when combined with physical measures *(Ewing & Brown, 2009)*.

5.4 ROAD DESIGN COUNTERMEASURES

Road and street design countermeasures can include reductions in lane widths, a road diet, installation of a center island or median, or reconstructing an intersection into a roundabout. Center islands or medians may help reduce 85th percentile speeds by an average of 7% and are associated with a 0.29 CMF. Roundabouts have been associated with a CMF of 0.213-0.58 and may be highly effective at managing speeds to improve safety *(Bagdade et al., 2012)*.

Gargoum et al. (2016) examined the relationships between the road and surrounding features and driver operating speeds on urban roads in Edmonton, Canada. Several factors were found to affect compliance. The effects of on-street parking, the presence of shoulders or medians, and the number of lanes varied depending on the road classification. For arterial roads, increasing the number of lanes and the presence of parking were positively correlated with speed limit compliance. In contrast, these features were negatively correlated with compliance for collector roads. The presence of medians and shoulders and adjacent agricultural or commercial land use were negatively associated with compliance for arterial roads. Posted speed limit was found to be positively correlated with compliance on both roadway types. In general, the researchers indicated the more spatially restricted drivers become, the more likely they are to comply.

5.4.1 Lane Width Reductions

Bagdade et al. (2012) found lane width reductions may decrease speeds by 1-3 mph for every foot that the roadway is narrowed down to a minimum of 10 feet, but recommends they should only be considered on lower speed roads.

According to *NACTO (2013)*, lane widths of 10 feet are appropriate in urban areas and have positive impacts on safety without impacting traffic operations by promoting slower driving speeds. If the road is a designated truck or transit route, an 11 feet wide curb lane may be necessary to accommodate the larger vehicles.

Fitzpatrick et al. (2001) found that lane width was a significant variable affecting the 85th percentile operating speed on tangent sections while excluding the posted speed limit from the model. One meter (3.3 foot) increase in lane width predicted speeds that were 15 km/h (9.4 mph) faster.

Stein & Neuman (2007) agree that narrower lane widths may help manage or reduce vehicle speeds, and may also shorten crossing distances for pedestrians. *AASHTO (2011)* suggests lane widths for urban roads to fall between 9 and 12 feet depending on the road classification. Potential adverse impacts on safety and operations due to lane widths narrower than the recommended range for urban arterial roads include sideswipe crashes, reduced free-flow speeds, or large vehicles off-tracking to adjacent lane or shoulder *(Stein & Neuman, 2007)*. The *Highway Capacity Manual (Transportation Research Board, 2010)* states that free-flow speeds on two-lane highways can be expected to decrease by up to 6.4 mph as lane width is reduced from 12+ feet to 9 feet and shoulder width is reduced from 6 feet to zero feet.

5.4.2 Road Diets

Road diets such as converting a four-lane undivided road to a three-lane with TWLTL road have potential for reducing speeds and are associated with a CMF of 0.47-0.71 *(Bagdade et al., 2012)*.

In addition to the analysis and calculation of the crash modification factors by *Chen et al. (2013)*, *Knapp & Giese (2001)* reviewed thirteen case studies and used CORridor SIMulation (CORSIM) software to investigate and develop feasibility factors and guidelines for a road diet of converting a four-lane undivided road to a three-lane with two-way left-turn lane (TWLTL) road. Conversions of such type have been proposed and implemented as an alternative to widening a roadway cross-section to improve safety and operations.

In the thirteen case studies, the total number of crashes was typically found to decrease when a four-lane road was converted to a three-lane with TWLTL road (17-62% for the case studies reviewed). The case studies also indicated there was a minor reduction in average or 85th percentile speeds following conversion, typically less than 5 mph. Additionally, a reduction in excessive speeding and total crashes was found.

Results of the CORSIM simulation showed a 0-4 mph reduction in average arterial speed over a wide range of peak-hour volumes (500-1,000 vehicles per hour per direction), access densities (0-50 points per mile per side), and access-point left-turn volumes (10-30% of through volume) following a conversion. Simulated arterial LOS decreased once bi-directional peak-hour volume reached 1,750 vehicles per hour. The researchers support the feasibility of such conversion when bi-directional peak-hour volumes are less than 1,500 vehicles per hour.

Knapp & Giese (2001) recommended the following additional considerations when determining the feasibility of converting a four-lane undivided road to a three-lane with TWLTL road:

- Roadway function and the environment – the goal is to match the levels of mobility and access needed with the actual road function. Conversions are generally feasible for minor arterial and major collector road classifications.

- Turning volumes and patterns – consideration of a three-lane with TWLTL conversion is recommended when a four-lane undivided road is already operating as a defacto three-lane road due to a high volume of left-turning traffic.

- Frequent-stop and slow-moving vehicles – due to the inability of passenger vehicles to legally pass on a three-lane road, slow moving vehicles or those which make frequent stops may greatly impact the mobility of through traffic.

- Weaving, speed, and queues – weaving or lane changing should not occur after the conversion of a four-lane undivided road to a three-lane with TWLTL road, but education and/or enforcement may be necessary if vehicles are incorrectly using the TWLTL. Results of the case study reviews indicated the potential to use such a conversion as a traffic calming measure due to the usual reductions in average speed and speed variability that were found. Delays and queues may be reduced by optimizing signal timing.

- Crash type and patterns – case study results indicated a potential for reductions in crash rate and crash severity following a conversion. The researchers suggest safety improvements may be due to a reduction in speed or speed variability, a decrease in the number of conflict points between vehicles, or improved sight distance for major-street left-turning vehicles.

- Pedestrians and bicycle activity – conversion reduces the number of conflict points between vehicles and crossing pedestrians and may allow wider lanes or space for dedicated lanes for bicycle traffic.

- Right-of-way availability, cost, and acquisition impacts – conversion to a three-lane with TWLTL road may eliminate or substantially reduce the need to acquire costly additional right-of-way compared to widening a four-lane undivided road except for possible driveway or intersection radii reconstruction needs.

- Other general impacts such as the potential shift of traffic volume to nearby parallel roads following a conversion; heavily used offset minor street or driveways which may produce conflicting overlapping turns within the center lane; parallel parking along the road which is generally not recommended when the road primarily serves a mobility purpose; and queues at at-grade railroad crossings which can be expected to approximately double following a conversion to a three-lane with TWLTL road.

5.4.3 Gateway Treatments

A gateway treatment may be used at the entrance to a town or village or to signify an area where lowered speeds are required. Gateway treatments use a combination of traffic control, road and street design, and traffic calming measures to call a driver's attention to a speed transition zone. Large signs, pavement markings, architectural features such as fencing or rock walls, and rumble strips which send tactile and audio feedback to the driver may all be used as part of a gateway treatment *(Global Road Safety Partnership, 2008)*. Gateway treatments may reduce speeds by an average of 5 mph *(Bagdade et al., 2012)*.

5.4.4 Roundabouts and Traffic Circles

Roundabouts and traffic circles direct traffic counterclockwise through an intersection and can be effective at reducing crash severity in intersections by reducing travel speed and reducing the angle between existing traffic within the roundabout or traffic circle and the entering traffic *(City of San Jose, 2001; Global Road Safety Partnership, 2008; OECD, 2006)*.

Roundabouts are typically used at higher volume intersections on collector and arterial streets. They may have mountable outer rings (truck aprons) to accommodate larger truck traffic *(Ewing & Brown, 2009)*.

A 1989 survey of crashes at 447 mini-roundabouts in England, Wales, and Scotland found that this intersection design was most commonly used on streets with speed limits of 30 mph or less and had a significantly lower overall crash rate than signalized intersections with equivalent speed limits. The survey also showed that four-arm mini-roundabouts have about the same crash involvement rate (crashes per million vehicles of that type entering the intersection) for bicyclists as conventional, four-legged, signalized intersections *(FHWA, 2013)*.

Roundabouts should have clear signing and highly visible centers and should ensure bicyclists are not squeezed by other vehicles in the intersection *(FHWA, 2013)*.

5.5 ENFORCEMENT COUNTERMEASURES

Shrestha & Shrestha (2016) found that most representatives from state DOTs interviewed agreed that police enforcement is the most effective method for speed limit compliance.

One such method of enforcement is the use of speed cameras. *Schechtman et al. (2016)* conducted roadside interviews of drivers in Israel for four years to judge the effects of speed camera installation on driving behavior. Analysis of the results showed that the percentage of respondents who expected the speed cameras to have a positive impact on traffic safety stayed relatively constant throughout the years, but the percentage reporting that the speed cameras influenced their driving behavior decreased over the years. However, the main reason indicated for obeying the speed limit was fear of enforcement which supports the use of speed cameras as an effective tool to impact behavior.

Bar-Gera et al. (2017) analyzed probe vehicle data obtained by GPS and cellular devices for the effects of speed enforcement cameras on operating speeds near camera sites and a range of distances upstream and downstream from them. Speeds were most affected within a 200m buffer zone around the camera site. Comparison of one month before activation to one month after indicated a modest decrease of the 85th percentile speed of 2.92 km/h (1.81 mph) while long term (11 months post activation) decreases were more significant at an average of 6.48 km/h (4.03 mph). As distance from the camera location increased, the amount of speed reduction gradually diminished. At 1500 m (0.93 mi), the average reduction was 1.7 km/h (1.05 mph) and 0.84 km/h (0.52 mph) for the upstream and downstream directions, respectively.

In 2015, the Insurance Institute for Highway Safety (IIHS) found that after 7.5 years since the implementation of speed enforcement cameras on residential streets and in school zones in Montgomery County, Maryland, mean speeds were reduced by 10% and the likelihood of exceeding the speed limit by more than 10 mph was reduced 62% *(Hu & McCartt, 2016, as cited in NTSB, 2017)*.

Goodwin et al. (2015) state that automated speed cameras have been consistently demonstrated to be effective for speed management and can substantially reduce injury and non-injury crashes as well as reduce average speeds. As of 2015, automated speed cameras were being used in approximately 134 jurisdictions in 12 states, the District of Columbia, and the U.S. Virgin Islands.

While enforcement by speed cameras may have positive effects on compliance, many drivers do not support their use. The survey administered by the AAA in 2017 indicated that just over half of respondents are strongly or somewhat opposed to their use *(AAA, 2018)*. Criticisms include that it violates rights of due process, equal protection, and privacy and that it may be used as a tool to generate revenue rather than promote safety *(NTSB, 2017)*.

The enforcement threshold (the lowest speed at which a violation will be recorded) of a speed camera is an important consideration. The *NHTSA (2008)* offers that 11 mph above the speed limit is an appropriate threshold as it targets those who drive substantially faster than the speed limit, but a lower threshold not less than 6 mph above the speed limit is appropriate in areas with low speed limits, especially where pedestrians and children may be present.

Miller et al. (2016) surveyed agencies in the US that employ automated speed enforcement about the enforcement thresholds used. The mean threshold used was 11 mph over the speed limit with a range for most road types of 6-15 mph over. The minimum threshold in school zones was lower for a few of the surveyed agencies and the mean threshold was nine mph. Tennessee reported they allow “zero tolerance” and begin ticketing at one mph over the speed limit.

In Edmonton, Canada, *Gargoum et al. (2016)* noted that a threshold of 10 to 15 km/h (6 to 9 mph) is generally applied before a traffic citation is issued.

Penalties for traffic citations vary throughout the world. GoCompare (a price comparison website for insurance in the United Kingdom) analyzed the lowest possible fines without added surcharges for three common traffic violations for 31 OECD countries *(Mohn, 2018)*. Fines in Australia, Canada, and the U.S. were taken as the median fine across states or provinces. Speeding violation fines were based on a violation of 13 mph above the maximum limit. The report showed the U.S. ranks 25th, making it one of the cheapest countries for speeding violations. The U.S. ranked even lower for the violation of using a mobile phone while driving and for driving through a red light at 31st and 30th, respectively.

British Columbia, Ontario, and Quebec, introduced legislation in 2010, 2007, and 2008, respectively, to combat excessive speeding through immediate suspension of driver’s license, vehicle impoundment, hefty fines, and demerit points. *Gargoum (2015)* was interested in how the legislation affected counts of fatal, injury, and property damage only (PDO) crashes through a time series analysis. Monthly crash counts were collected for each province before and after the new legislation and divided by severity category. Exposure was based on a surrogate measure for VKT by using monthly motor vehicle fuel sales. In British Columbia and Ontario, a statistically significant drop in fatal crashes occurred following the new legislation. In Quebec, a statistically significant drop in injury, PDO, and total crashes was observed. The author adds that additional driving laws pertaining to distracted driving and impaired driving had also been implemented at the same time and may have been partially responsible for the drops.

Enforcement alone may be an expensive measure to reduce crashes significantly. For example, Figure 3 shows data used by Elvik *(2012)*, to develop a crash modification function for speed enforcement intensity. Speed enforcement improves compliance and reduces crashes but there are clear diminishing returns. If enforcement is doubled the expected crash reduction factor is approximately 0.83 and if enforcement is quadrupled the expected crash reduction factor is in the range of 0.65-0.72 approximately.

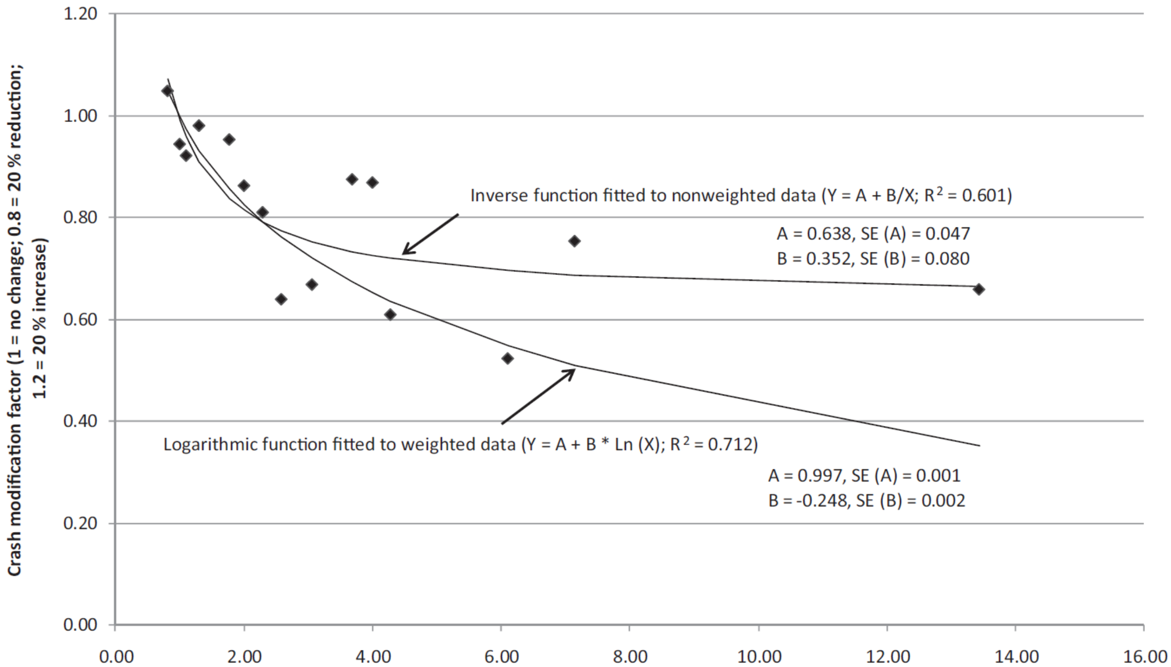

Figure 5.1: Effects of changes in enforcement level on crash modification factors (Reproduced from *Elvik 2012*).

5.6 EDUCATION COUNTERMEASURES

As part of a holistic speed management campaign, the *NHTSA (2014)* supports the implementation of an education strategy aimed at increasing the public's understanding of the risks associated with speeding through carefully selected communication channels such as TV and radio, partner dissemination, and social media.

A multi-level provisional licensing scheme has been utilized in some jurisdictions where a novice driver may be subject to decreasing levels of restrictions as they pass up through the levels before finally receiving a full license *(Global Road Safety Partnership, 2008)*.

From a telephone questionnaire survey of approximately 1100 Spanish drivers, *Alonso et al. (2015)* found that the perception of crash risk due to speeding was significantly lower for drivers who admitted to speeding more frequently, those who had been involved in a traffic crash, or those who had a record of driving penalties. Additionally, results indicated male drivers perceived the risk of crash involvement due to speeding lower than females. In light of these results, the authors noted a need for education and interventions designed according to the characteristics of risk groups.

Hatakka et al. (2002) explain that driver education should help the student become aware of and evaluate their personal tendencies that affect their driving behavior regarding possible risk increasing factors such as self-enhancement, sensation seeking, aggressive driving, not obeying rules, unsuitable speed adjustment, and others. The authors formulated a framework outlining goals for driver education according to a four-level hierarchy of driver behavior. Basic vehicle maneuvering skills is the lowest level of the hierarchy. One level up resides skills for mastery of traffic situations including predicting others' behavior and communicating their own. The third level involves determining goals and context of driving such as for what purpose, which route, with whom, and what time to drive. The highest level relates to awareness of goals for life which pertains to how personal values, lifestyle, and self-control affect driving behavior. Driver education is hypothesized to focus heavily on the two lower levels and that one potential method to improve road safety and compliance with speed limits is enhanced educational efforts emphasizing self-awareness and self-evaluation skills at the higher levels of the hierarchy.

5.7 SPEED MANAGEMENT TECHNOLOGY

Speed management technology may be used within a vehicle to inform drivers of speed limits, to limit the maximum speed at which a vehicle can be operated, or to record data to enhance crash analysis efforts *(Global Road Safety Partnership, 2008)*. Speed management technology can also be found in the form of software which helps engineers and practitioners make effective speed management decisions *(Aarts et al., 2009)*.

Road speed limiters (RSL) are required by the European Community on trucks and buses, including light commercial vehicles, and are also used in Australia. Road speed limiters only limit the maximum speed a vehicle can travel and therefore do not reduce speeding on roads with speed limits below the RSL's settings *(Global Road Safety Partnership, 2008)*.

Electronic data recorders record operating characteristics such as speed, acceleration, and airbag deployment for a few seconds prior to, during, and after a crash. The data can be retrieved for more detailed analysis *(Global Road Safety Partnership, 2008)*.

Intelligent speed adaptation (ISA) is a technology that communicates the speed limit to the vehicle from a database of speed limits based on the vehicle's location detected by GPS. There are three basic types of ISA. ISA may be informative only, communicating the prevailing speed limit to the driver and warning when the speed limit is exceeded. Voluntary supportive ISA is found in features such as cruise control where the driver can choose to set the maximum speed and operates without a speed limit database. A mandatory supportive ISA system intervenes whenever the vehicle exceeds the speed limit *(OECD, 2006; Global Road Safety Partnership, 2008)*.

5.8 SPEED AND URBAN MOBILITY

From a mathematical standpoint, higher travel speeds lead to decreased travel times. However, the relationship between travel time and speed is relatively complex, and road users in urban areas generally overestimate the actual time savings associated with higher travel speeds due to the presence of intersections, pedestrians, rail crossings, and delays at traffic signals *(OECD, 2006; Archer et al., 2008)*. Lack of traffic signal coordination and critical lane volume to capacity ratios usually affect delay and travel time variations in urban areas as well *(Archer et al., 2008)*.

A study in France measured travel times along a 7.6 km (4.7 mi) route containing 28 traffic signals and found that a 40% reduction in average travel speed only led to a 20% increase in travel time. The increased travel time was due in part to the higher number of times the vehicles traveling at the slower speed stopped at traffic signals *(ZELT, 2004 as cited in OECD, 2006)*. However, this result can be clearly affected by the performance of the traffic signal coordination system and the relationship between coordination speed and posted speed limit.

Overall, the impact of lowering speed limits on travel times remains questionable, and congestion problems may be relieved to a certain extent by using well-coordinated traffic signals or other forms of traffic management strategies *(Archer et al., 2008)*.

Studies have also shown that in built-up areas, reducing the average travel speed from 50 km/h (30 mph) to 30 km/h (20 mph) was not associated with any significant decreases in traffic flow capacity, suggesting that speed management is not necessarily incompatible with mobility needs *(OECD, 2006)* when capacity is mainly limited by signal timing.

5.9 SUMMARY

Speed management should consider the needs and safety of all road users, particularly pedestrians, bicyclists, and other vulnerable road users. A strategic program includes elements of engineering, education, enforcement, and emergency services and it should continuously updated and monitored *(OECD, 2006)*.

Traffic calming countermeasures are often implemented on roads where a reduction in vehicle speed or volume is desired. Traffic calming consists of a wide variety of countermeasures encompassing street closures, installation of vertical impediments, horizontal diversions, street narrowing, circular intersection designs, pavement markings, and traffic control or regulatory measures.

Traffic calming countermeasures are generally restricted to local and collector roads with speed limits of 30 mph or less, although some jurisdictions make exceptions. The mobility of emergency response vehicles is an important consideration when making decisions around which countermeasures to apply. Maintenance and landscaping costs as well as snow removal needs should also factor into the decision-making process.

Speed limits are the most common method for managing traffic speeds but studies have indicated they are not sufficient on their own. Speed limits may be more effective when combined with road design countermeasures. Lane width reductions, road diets, and roundabouts have all demonstrated positive safety impacts by reducing vehicle speeds and/or reducing crash frequency or crash severity.

Enforcement is cited as an effective speed management method, especially for decreasing excessive speeding behavior and crashes at locations with a high number of crashes. Automated camera systems are commonly used throughout many jurisdictions worldwide in enforcement efforts. The threshold before a citation is issued ranges between 6 to 15 mph over the posted speed limit for most road types. The penalties imposed for violations of the speed limit may influence the effectiveness of enforcement efforts with higher penalties associated with reductions in excessive speeding.

Driver education also play an important role in speed management. Multi-level provisional licensing schemes are utilized in some jurisdictions to help novice drivers learn under decreasing degrees of supervision or restriction as they complete each level. Currently, driver education is highly focused on basic vehicle maneuvering skills and mastery of traffic situations. Teaching skills of self-awareness and self-evaluation of driving behaviors in relation to the goals and context of driving and personal values may be help reduce speeding occurrences. Designing education and interventions according to characteristics of risk groups may also be effective for reducing speeding behavior.

In-vehicle speed management technologies are also commonly utilized to manage speed. Road speed limiters restrict the maximum speed a vehicle may travel, but are not effective tools for roads with speed limits below the speed limiter's settings. Intelligent speed adaptation (ISA) technologies come in three general types – informative only, voluntary supportive, and mandatory supportive, providing information on speed limits, driver selected speed control, and intervention, respectively.

Speed management is essential for the safety of all road users, but drivers may view countermeasures to be mobility-restrictive by increasing travel times. However, the relationship between speed and travel time is relatively complex. In urban areas, travel times are likely to be more affected by congestion, the presence of intersections, a lack of traffic signal coordination, pedestrians, and rail crossings rather than posted speed limits. However, there may be circumstances, specific corridors, or road networks where changes in speed limits may significantly affect travel times.

6.0 SPEED ZONE GUIDELINES BASED ON THE 85TH PERCENTILE SPEED

The need to control driving speeds started as early as 1901 and the use of operating speeds of motorized vehicles to adjust speed limits started as early as the 1930s and 1940s to respond to public demands for higher speeds *(TRB, 1998)*.

6.1 SIGNIFICANCE OF THE 85TH PERCENTILE SPEED

Guidance from the current version of the *Manual on Uniform Traffic Control Devices* (MUTCD) *(FHWA, 2009)* which is expected to be updated around springtime of 2019, Section 2B.13, paragraph 12 states, "When a speed limit within a speed zone is posted, it should be within 5 mph of the 85th percentile speed of free-flowing traffic."

In a review of state DOT guidelines for speed zone establishment, *Shrestha & Shrestha (2016)* found that the most common factor used by states in determining speed limits is the 85th percentile operating speed. The prevailing belief supporting the utilization of the 85th percentile of is that the majority of drivers naturally choose safe and reasonable speeds according to the given conditions and setting the limit near the speed at which 85% of drivers travel at or below improves compliance and reduces the burden of enforcement. Early research efforts, from the 1950s, hypothesized that the 85th percentile of vehicles operating speeds minimized crash rates. The claim that the 85th percentile speed minimizes crashes is no longer accepted; instead, it is believed that higher speeds increase crash rates but the exact relationship is complex and involves many factors *(NTSB, 2017)*.

While using the 85th percentile speed is widely recommended as the basis for setting speed limits, the method has received criticism due to the assumption that drivers are aware of and select the safest speed, however, drivers are generally bad at accounting for the externalities of their driving. An additional criticism against the method is the belief that it may lead to an upward drift in average operating speed over time *(Forbes et al., 2012)*. In some cases, setting the speed limit to the 85th percentile speed may be perceived as a barrier to crash and injury reduction efforts *(Lahausse et al., 2010)*. An example of this perception is held by city council members in Los Angeles, where speed limits were raised on 102 miles of city streets after outdated speed surveys were updated, which was necessary under California law for radar or laser speed enforcement *(Fonseca, 2018)*.

6.2 ENGINEERING STUDIES

The current version of the MUTCD *(FHWA, 2009)* Section 2B.13 paragraph 6 says that maximum speed limits applicable to rural and urban roads are generally established either through state statutes or as altered speed zones based on engineering studies.

Where statutory speed limits are deemed inappropriate or when speed-influenced crash history or other safety concerns are prevalent for a roadway section, a request to reduce the speed limit may be placed by members of the community or by the municipality to the governing roadway authority. In such cases, the appropriate speed limit is generally determined by conducting an engineering and traffic study.

There is currently no universally prescribed method for conducting an engineering study, but *Forbes et al. (2012)* highlights the following steps taken by many state DOTs. Roadway geometry, environment, special features, and traffic characteristics should be reviewed. Vehicle operating speeds should be observed and recorded in ideal weather under free-flow conditions and used to determine the 85th percentile and other speed characteristics. The crash history for the road section and any other special or unusual conditions should be reviewed.

6.2.1 Adjustments to 85th Percentile Speed

A recent survey by the National Committee on Uniform Traffic Control Devices (NCUTCD) Task Force found that professionals who perform speed studies rarely rely only on the value the 85th percentile speed for setting speed limits *(Fitzpatrick et al., 2019)*.

The current version of the MUTCD *(FHWA, 2009)* Section 2B.13 paragraph 16 lists factors that may be considered in the establishment of speed limits. These factors include:

- Road characteristics, shoulder condition, grade, alignment, and sight distance;
- The pace;
- Roadside development and environment;
- Parking practices and pedestrian activity; and
- Reported crash experience for at least a 12 month period.

Shrestha & Shrestha (2016) compiled a list of factors considered in establishing speed limits mentioned in literature and through interviews with DOT representatives and found many of those listed in the MUTCD reiterated. Political and public influence, bicycle usage, and access density were also listed.

Results of the survey discussed by *Fitzpatrick et al. (2019)* found that practitioners often consider the context of location, context of land use, and facility classification type to be important, and reiterated bicycle and pedestrian activity, crash history, road geometry, and access management as key factors to consider when setting a speed limit.

The *California MUTCD (California Department of Transportation [Caltrans], 2018)* states that physical conditions such as road width, curvature, grade, surface conditions, or any other condition readily apparent to the driver would not require special downward speed adjustments. However, the residential density may be considered if there are 13 or more separate dwellings or business structures on one side or 16 or more on both sides, combined, within a quarter-mile section. If the section of road is longer than a quarter-mile, the residential density may be considered if the ratio of separate dwellings or business structures to length of road is equal to the aforementioned ratios (Section 2B.13, paragraph 29). Pedestrian and bicyclist safety, most recent two-year collision record, and intersection spacing may also be considered when qualifying an appropriate speed limit.

A summary of adjustment factors is given in Table 6.1.

Forbes et al. (2012) indicates that adjustments for roadway characteristics and crash history should normally not exceed 7 mph below the 85th percentile but may be as much as 10 mph lower for instances of narrow roadway or shoulder widths, limited sight distances, high potential for encountering active travelers, high driveway density, or if the crash rate is higher than that of similarly classed roadways. Exact quantitative criteria are rarely given for such adjustments and analysts are advised to use "engineering judgment."

The NCUTCD submitted a proposal for changes to Section 2B.13 of the MUTCD in January 2019 *(NCUTCD, 2019)* following the results of the survey they conducted, as discussed by *Fitzpatrick et al. (2019)*. Proposed changes include:

- Indicate that the speed distribution (including 85th percentile and pace speed) from an engineering study is just one of the factors to be considered when setting speed limits;
- Re-enforce there are many factors to be considered other than the speed distribution by changing the language from factors that "may" to "should" be considered;
- Include lane widths, medians, driveways, land use, functional classification, and past study data as factors to consider;
- Specify consideration for the types of road users, such as pedestrians and adding "bicyclists," when setting speed limits;
- Limiting the specificity of using the nearest five mph increment to the 85th percentile speed to set speed limits to freeways, expressways, and rural highways;
- Guidance for performing a speed study at the approximate middle of a segment if the signal spacing is less than one mile.

It should be noted that as of the time of this writing, these revisions have not yet been approved by the FHWA and therefore do not constitute official MUTCD standards, guidance, or options *(NCUTCD, 2019)*. They have been included in Table 6.1 and signified with an asterisk *.

Table 6.1: Summary of Adjustment Factors.

FACTOR	SOURCE				
	CA MUTCD (2018)	*Fitzpatrick et al. (2019)*	*Forbes et al. (2012)*	*MUTCD (2009)*	*Shrestha & Shrestha (2016)*
Access density		x	x		x
Alignment		x		x	x
Grade				x	
Intersection spacing	x				
Residential density	x				
Shoulder conditions	x		x	x	
Sight distance	x	x	x	x	
Superelevation	x				
Facility classification		x		x*	
Land use context		x		x*	
Parking practices				x	
Bicycle activity	x	x	x	x*	x
Pedestrian activity	x	x	x	x	x
Crash experience	x	x	x	x	x
Pace				x	
Political/public influence					x

* Indicates factors to be included in a revised copy of the MUTCD, as proposed by the NCUTCD *(NCUTCD, 2019)*.

6.2.2 Data Collection Practices and Methods

In the research by *Shrestha & Shrestha (2016),* the consensus of states is to use spot speed data to calculate prevailing speed parameters of vehicles. Laser or radar guns, pneumatic tubes, and on-road sensors are commonly used in speed data collection. High-speed digital video has also been used in some studies in addition to other methods *(Bassani et al., 2014; Bassani et al., 2016)*. A summary of instrument types used and other considerations for speed data collection is available in Table 6.2.

Table 6.2: Summary of Speed Data Collection Practices.

AUTHOR	SPEED DATA COLLECTION METHODS				
	Instrument	**Duration**	**Number of observations**	**Number of segments**	**Special considerations**
Bar-Gera et al. (2017)	Probe vehicle GPS		13,000	21 + 12 control	
Bassani et al. (2014)	Laser gun, high-speed digital video		5339	16	Headway greater than 5s
Bassani et al. (2016)	Laser gun, high-speed digital video		10011	9	Headway greater than 5s
Dinh & Kubota (2013)	Stalker ATS radar gun		5359	85	Good weather, daytime, free-flow
Eluru et al. (2013)	NC-97, NC-100, NC-200	5 days for local, 7 days for arterial	480 local, 1456 arterial	49 local, 71 arterial	
Fitzpatrick et al. (2001)	Laser gun	Maximum 3 hours per site	Goal of 100 per site	19 curve, 36 straight	Headway greater than 5s, daytime
Fitzpatrick et al. (2016)	Cellular GPS (Ubipix), pneumatic tubes with ATRs, LiDAR		20 by GPS, 100 by LiDAR	1	
Gargoum & El-Basyouny (2016)	Vaisala Nu-Metrics NC-200	5 years	35,000	353	Headway greater than 5s
Gargoum et al. (2016)	Vaisala Nu-Metrics NC-200	3-8 days per site for 5 years	35,000	600	Headway greater than 2s
Himes et al. (2013)	On-pavement sensor	2-6 hours per site	357 one-hour intervals	79	Daylight, good weather
Islam et al. (2014)	Vaisala Nu-Metrics NC-200	7 months, continuous	24, 000, 000	51 + 14 control	Headway greater than 2s, no adverse weather
Schechtman et al. (2016)	Pneumatic tubes			14	
Taylor et al. (2000)	Automatic roadside measuring equipment	9:30-16:30		100	Bad weather and temporary events (e.g. roadwork) avoided
Wang et al. (2018)	Floating car GPS (taxi)		702	234	

A limitation of using spot-speed data to calculate speed parameters is that it may not be representative of the entire section under study. Speed data collection locations need to be chosen carefully to capture an accurate representation of maximum operating speeds. *Dinh & Kubota (2013a)* used radar guns connected with laptop computers to record continuous speed data to determine the location within the study segments where most drivers reached their maximum speed. It was found that most drivers accelerated to maximum speed before decelerating and that maximum speeds were achieved after passing the midpoint between the two intersections that defined the segment length.

With the rise of portable technology in recent years, *Fitzpatrick et al. (2016)* studied the utility of GPS smartphone apps to collect continuous speed data. Speed data from volunteer drivers equipped with the Ubipix app was compared to data obtained from pneumatic tubes with automated traffic counters and LiDAR spot surveys. The data from the Ubipix app was found to be consistent with both the pneumatic tubes and LiDAR surveys indicating an opportunity to utilize crowd-sourced data to improve road safety and reevaluate speed zones.

Wang et al. (2018) utilized high-frequency taxi-based GPS technology to capture the spatio-temporal distribution of speed along a road section and *Bar-Gera et al. (2017)* employed probe vehicle GPS data to study the halo effect of speed enforcement cameras.

Additional considerations for speed surveys are the number of study locations, time of data collection, and the number of vehicles surveyed. Again, there is little consensus on specific requirements concerning these considerations. The reviews and surveys by *Shrestha & Shrestha (2016)* yielded recommendations of a minimum of 50 (preferably 100) vehicles in each lane in each direction or at least four hours of collection time for low volume roads and to avoid rush hours, weekends, holidays, or special events.

Geometric, road, and roadside characteristics are often recorded by conducting site visits, but some studies have utilized GIS maps or technologies such as Google Street View *(Gargoum & El-Basyouny, 2016; Eluru et al., 2013; Gargoum et al., 2016; Wang et al., 2018).*

6.3 STATE GUIDELINES

6.3.1 California Guidelines

The *California MUTCD (Caltrans, 2014)* directs speed limits to be established at the nearest five mph increment to the 85th percentile speed of free-flowing traffic. Exceptions to this direction must be documented and justified in an engineering and traffic survey and are as follows:

- The posted speed may be reduced by five mph from the nearest five mph increment of the 85th percentile speed;
- The posted speed limit may be rounded down to the nearest five mph increment below the 85th percentile speed if the nearest five mph increment to the 85th percentile speed would otherwise require rounding up (Section 2B.13, paragraph 12a).

Conditions which are readily apparent to the driver in the absence of other factors would not require a special reduction in speed limit. Factors for justifying a speed limit below the 85th percentile speed include but are not limited to: residential density (quantified above in Section 5.2.1), most recent two-year collision record, design speed, safe stopping sight distance, superelevation, shoulder conditions, profile conditions, intersection spacing, and pedestrian traffic in the roadway without sidewalks (Section 2B.13, paragraph 30).

When conducting an engineering and traffic survey, speed measurements should be of unimpeded traffic. Radar or other devices capable of accurately distinguishing and measuring the speed of free-flowing vehicles may be used. Speed measurements should be taken during off-peak hours between peak hours on weekdays under fair weather conditions. The minimum sample size is 100 vehicles and in no case should the sample size be less than 50. Speed zoning should be in 10 mph increments except in urban areas where five mph increments are preferred (Section 2B.13, paragraph 26).

6.3.2 Massachusetts Guidelines

The State of Massachusetts requires an engineering study to be conducted to establish posted speed limits that vary from given statutory limits *(Massachusetts Department of Transportation, 2017)*. Statutory speeds in Massachusetts are:

- 20 mph in a legally established school zone
- 25 mph in a thickly settled or business district that is not a State Highway; 30 mph otherwise
- 40 mph on an undivided highway outside of a thickly settled or business district
- 50 mph on a divided highway outside of a thickly settled or business district

A thickly settled or business district is defined by MGL c. 90 § 1 *(MGL, 2018)* as "the territory contiguous to any way which is built up with structures devoted to business, or the territory contiguous to any way where dwelling houses are situated at such distances as will average less than two hundred feet between them for a distance of a quarter of a mile or over."

Three trial runs in each direction of the proposed speed zones should be conducted, and the median speed at each tenth mile is used to draw a speed curve. The speed curve may be used to determine the location for the spot speed survey which should be conducted in free-flow conditions on a weekday in ideal weather. Speeds should be measured by a radar or laser gun. A minimum of 100 observations should be recorded in each direction. For low volume roads, two hours of observations should be collected. Existing geometric conditions, traffic volumes, and warning signage should be recorded. Five years of crash history should be reviewed.

The determined safe speed ranges from seven mph below the observed 85th percentile speed to the minimum value of either the sight distance design speed or the observed 95th percentile speed.

The 85th percentile speed is generally rounded to the nearest five mph increment and given as the recommended limit. Conditions that may warrant adjustments to the 85th percentile include sections with unusual crash rates attributed to excess speed, sections where lateral physical constraints exist, or where the observed 85th percentile speed is similar at the start and end of a section but is slightly higher or lower in the middle. In all conditions, the final speed limit should fall within the determined safe speed range and be a multiple of five.

6.3.3 New York Guidelines

Guidelines from the New York Department of Transportation state the chosen speed limit must be realistic in terms of existing traffic speeds. For most cases, the nearest five mph increment to the 85th percentile speed is sufficient, established by conducting a spot speed survey via radar. If safety concerns related to non-motorists are present, appropriate mitigation countermeasures should be implemented. Examples of such countermeasures include signing and marking improvements, addition or improvement of sidewalks, shoulders, bike lanes, and high visibility crosswalks, brush and tree cutting for visibility, lane narrowing, or other traffic calming elements.

A floating vehicle check may be conducted by driving the road several times in each direction to obtain an appropriate speed for ideal, free-flow conditions as an alternative to using the 85th percentile speed from the radar survey. Crash history should be reviewed and considered in selecting a speed limit when using either of the aforementioned methods.

If there is justification to establish a speed limit below the 85th percentile, it should not be set lower than three mph below the upper limit of the 10 mile pace speed and it should not place more than one-third of traffic in technical speed violation, unless documentation is provided to justify an exception.

A third option for selecting a speed limit is the FHWA's USLIMITS2 web-based tool. Care should be taken in considering the sample size of the speed study as outliers have a greater potential to impact results when the sample size is well under 100 vehicles. *(New York Department of Transportation, 2017).*

6.3.4 Oregon Guidelines

State statutes firstly govern speed limits in Oregon. Statutory speeds established for urban environments are as follows *(ORS 811.111)*:

- 15 mph for alleys and narrow residential roadways
- 20 mph in business districts and school zones
- 25 mph through residential districts and public parks

State statute ORS 810.180 also grants the Department of Transportation authority to establish speed limits on other public roadways in Oregon given that an engineering and traffic study is conducted. *(ODOT, 2014; ORS 810.180.)*

Unlike the MUTCD guidelines, the *Oregon Speed Zone Manual* (*ODOT, 2014)* indicates that "the engineering study will consider other factors such as:" geometric features, pedestrian and bicycle movements, type and density of adjacent land use, enforcement, crash history, public testimony, traffic volumes, and accesses.

The *Oregon Speed Zone Manual* (*ODOT, 2014)* provides guidelines on conducting engineering and traffic studies as well as recommending an appropriate speed limit given the results of those studies. Spot speed studies should be performed in normal weather during non-peak daylight hours. Only free-flow vehicles, defined as having a headway of four seconds or more, should be recorded, with trucks and commercial vehicles recorded separately. A minimum of 75 vehicles in each direction or a maximum of three hours of collection time for low volume roads should be recorded. Bicycles and pedestrians traveling along the roadway should also be tallied. The manual instructs the designated authority to base the recommended speed on the observed 85^{th} percentile speed and take into consideration roadway characteristics, roadside development demands, and crash history when rounding to the optimum five mph increment. Recommendations for streets and highways within city limits are allowed to vary from the 85^{th} percentile speed by no more than 10 mph when the ADT is greater than 400 vehicles.

6.4 SUMMARY

Speed zone guidelines have traditionally instructed engineers and practitioners to base speed limits on the 85th percentile free-flow operating speed. The 85th percentile was chosen out of the belief that the majority of drivers naturally choose safe and reasonable speeds according to the given conditions. By setting the speed limit at the 85th percentile, speed limit compliance is improved and the burden of enforcement is reduced. The method of basing a speed limit on the 85th percentile has been widely criticized, mostly recently, due to the belief that it may create an upward drift in speed over time and because drivers are generally bad at accounting for the externalities of their driving.

When a statutory speed limit is deemed inappropriate, guidelines direct engineers and practitioners to perform an engineering study by collecting relevant geometric, environmental, and traffic characteristics of the road. A traffic speed survey of vehicles under free-flow conditions is conducted in ideal weather, during day-time off-peak hours and the 85th percentile operating speed is calculated. The minimum recommended number of observations to collect is 50 with a preference for 100. Laser or radar guns, on-road sensors, and pneumatic tubes are commonly used instruments to collect speed data. Geometric, road, and roadside characteristics are generally recorded during site visits.

While guidelines instruct that the speed limit be set at the nearest five mph increment to the 85th percentile speed, some adjustments to that speed are allowed based on road characteristics, alignment, roadside environment, and reported crash history for a minimum of one year. Surveys of engineers and practitioners found that bicycle and pedestrian usage levels, access density, land use and location context, and facility classification type are also commonly referenced to make adjustments to the 85th percentile speed. Guidelines vary slightly on the amount of adjustment allowed, with a maximum of ten mph below the 85th percentile speed.

7.0 ALTERNATIVE SPEED ZONING APPROACHES

This chapter discusses alternative approaches to set posted speed limits. By “alternative” it is meant substantially different from the traditional methods based on the 85th percentile of free-flow operating speeds.

7.1 USLIMITS2

USLIMITS2 is a knowledge-based expert system developed by the FHWA to assist engineers and practitioners in determining safe and consistent speed limits for all roadway types. It was developed from prior research, consultation with practitioners and experts, and feedback from a first-generation system by the Australian Road Research Board *(Forbes et al., 2012)*.

The web tool guides users through the data input process and employs a decision algorithm to recommend a speed limit for the given section. The decision rules were developed using information obtained from surveys and face to face meetings with an expert panel and the NCHRP panel, and lessons learned from the original USLIMITS program *(Srinivasan et al., 2006)*.

Based on the roadway type to be analyzed, USLIMITS2 requires specific site characteristic inputs. Annual average daily traffic, current statutory limits, crash statistics, and both 50th and 85th percentile operating speeds are required for all road type designations. For road sections in developed areas, the area type, number of through lanes, number of driveways, number of traffic signals, the presence of on-street parking, the extent of pedestrian or bicycle activity, and whether the section is one-way are all necessary inputs *(FHWA, 2017)*.

Crash data for at least three years are recommended and if less than one year is available, the program suggests additional data collection before repeating the process. Total crash rate and rates of injury and fatal crashes are calculated per 100 million vehicle miles and compared to the average rates for similar roads in the jurisdiction if given, or to default values from the Highway Safety Information System.

The tool calculates a speed based on the safety surrogates selected for the given roadway type or from the results of the crash module. According to the decision flowchart for road sections in developed areas in Appendix K of the USLIMITS2 documentation, the speed limit recommended from the safety surrogate measures is determined as follows *(Srinivasan et al., 2006)*:

- Closest 5-mph multiple to the 50th percentile if any of the following conditions are met:
  - Signals per mile > 4
  - Pedestrian or bicycle activity is High

- Parking activity is High
- Driveways per mile > 60

- Rounded down 5-mph multiple of the 85th percentile if the following conditions are met:
    - Driveways per mile > 40 and ≤ 60
    - Signals per mile > 3
    - Area type is "commercial" or "residential collector"
- Closest 5-mph multiple to the 85th percentile otherwise.

The speed limit recommended from the results of the crash module are as follows:

- Closest 5-mph multiple of the 85th percentile if Crash Level is Low
- Higher of the rounded down 5-mph multiple of 85th percentile and the closest 5-mph multiple of 50th percentile if Crash Level is Medium
- Lower of the rounded down 5-mph multiple of 85th percentile and the closest 5-mph multiple of 50th percentile if Crash Level is High.

The lower of the results calculated from the safety surrogate and crash modules are used to determine the final recommended speed limit which lies between a minimum of 20 mph to a maximum of 50 mph.

While USLIMITS2 is easily accessible online for engineers and practitioners to use, results of the survey discussed in *Fitzpatrick et al. (2019)* showed that for participants who have conducted at least one speed study, only 20% have used the system. Participants with a lot of experience or many speed limit studies tend to use more the USLIMITS2 tool.

7.2 SACREDSPEED SPEED MANAGEMENT ALGORITHM

Aarts et al. (2009) describes an algorithm called SaCredSpeed to guide speed management decisions. According to *Aarts et al. (2009)* SaCredSpeed is based on scientific knowledge of safe speeds and speed management and credibility. SaCredSpeed consists of three individual algorithms: evaluation of the safe speed versus the speed limit or operating speed (90th percentile by default), determining the credibility of the speed limit from the road layout, and assessing enforcement needs if operating speed data is available.

Safe speeds are determined by road design characteristics and the legal traffic speed framework. In Sweden and the Netherlands, 30 km/h (20 mph) is considered the safe speed for urban access roads due to the presence of vulnerable road users *(Aarts et al., 2009)*.

The credibility of speed limits is questioned when operating speeds are higher than the posted speed limit or the safe speed (determined from the first algorithm) by comparing the road's design and layout characteristics to a host of features which have been identified in previous research to affect speed limit credibility. The influences (accelerant or decelerant) of each characteristic or factor are added together to estimate the overall effect. Equal numbers of accelerators and decelerators produce no overall effect, but a credibility issue may exist if the number of accelerators is greater than the number of decelerators. Once these three algorithms are completed, recommendations for speed management measures are given depending on the target speed chosen by the algorithm user (*Aarts et al., 2009)*.

7.3 ALTERNATIVE DESIGN APPROACHES

The FHWA has recommended that the design speed of a roadway should take into consideration the anticipated operating speeds and posted speed limits. "In urban areas, the design of the street should generally be such that it limits the maximum speed at which drivers can operate comfortably, as needed to balance the needs of all users," as stated in a memo on behalf of the FHWA regarding the relationship between design speed and posted speed *(Federal Highway Administration, 2015)*.

The NCHRP Report 839, *A Performance-Based Highway Geometric Design Process (Neuman et al., 2016)* indicates that recent advances in traffic and safety engineering allow for greater flexibility in the design process which can be used to meet the needs of multiple stakeholders. Some of the relevant alternative design concepts that are most relevant to this review include:

- Complete streets where the design concept has shifted towards providing for the safe mobility of all users. A complete street includes elements such as sidewalks, bicycle lanes, exclusive bus lanes, accessible transit stops, safe crossings for pedestrians (e.g. curb extensions and median islands), etc.

- Context sensitive design or a context sensitive solution puts priority on ensuring that the roadway design fits well with the area and strive towards a joint stakeholder vision of the shared space.

- Performance-based design incorporates a design process that explicitly balances operational and safety performance measures based on the Highway Safety Manual and crash reduction factors.

- Safe systems approaches, which are related to vision zero approaches, were first developed in Europe and Australia/New Zealand. A safe system approach is more holistic and all aspects of a transportation system (users, vehicles, infrastructure, and speed limits) are taken into account and measures are taken to reduce/eliminate traffic fatalities.

According to the *Institute of Transportation Engineers (2017)* report to implement context sensitive designs on multimodal roadways, street design should be used as "a language for communicating desired operating speed means designing toward a designated target speed, or the speed at which the community desires motorists to travel." An example of table that links target speeds and context design for bicycle facilities is provided by the *National Association of City Transportation Officials (2017)*; the table shown below contains in the first column the target motor vehicle speed. This guidance does not mention the words "speed limit" or "speed zone" but indicates that:

" † Setting 25 mph as a motor vehicle speed threshold for providing protected bikeways is consistent with many cities' traffic safety and Vision Zero policies. However, some cities use a 30 mph posted speed as a threshold for protected bikeways, consistent with providing Level of Traffic Stress level 2 (LTS 2) that can effectively reduce stress and accommodate more types of riders.[18]"

Contextual Guidance for Selecting All Ages & Abilities Bikeways

Roadway Context				All Ages & Abilities Bicycle Facility
Target Motor Vehicle Speed*	**Target Max. Motor Vehicle Volume (ADT)**	**Motor Vehicle Lanes**	**Key Operational Considerations**	
Any		*Any*	*Any of the following:* high curbside activity, frequent buses, motor vehicle congestion, or turning conflicts‡	**Protected Bicycle Lane**
< 10 mph	Less relevant	No centerline, or single lane one-way	Pedestrians share the roadway	**Shared Street**
≤ 20 mph	≤ 1,000 – 2,000		< 50 motor vehicles per hour in the peak direction at peak hour	**Bicycle Boulevard**
≤ 25 mph	≤ 500 – 1,500			
	≤ 1,500 – 3,000	Single lane each direction, or single lane one-way	Low curbside activity, or low congestion pressure	**Conventional or Buffered Bicycle Lane, or Protected Bicycle Lane**
	≤ 3,000 – 6,000			**Buffered or Protected Bicycle Lane**
	Greater than 6,000			**Protected Bicycle Lane**
	Any	Multiple lanes per direction		
Greater than 26 mph†	≤ 6,000	Single lane each direction	Low curbside activity, or low congestion pressure	**Protected Bicycle Lane, or Reduce Speed**
		Multiple lanes per direction		**Protected Bicycle Lane, or Reduce to Single Lane & Reduce Speed**
	Greater than 6,000	*Any*	*Any*	**Protected Bicycle Lane, or Bicycle Path**
High-speed limited access roadways, natural corridors, or geographic edge conditions with limited conflicts		*Any*	High pedestrian volume	**Bike Path with Separate Walkway or Protected Bicycle Lane**
			Low pedestrian volume	**Shared-Use Path or Protected Bicycle Lane**

Figure 7.1: Contextual bikeway design guidance (Reproduced from National Association of City Transportation Officials, 2017)

Oregon DOT design Guide Appendix L and Bicycle and Pedestrian Design Guide also provides context sensitive design, see figure below. This figure is accompanied by a separation context matrix or table that provides context in terms of land use, traffic speed/volume, roadway characteristics, and bicycle demand indicators. Mode share and active user comfort can be another design goal, for example, cyclists comfort increases as commercial vehicles and motorized traffic volumes decrease and is significantly higher for separated paths and bicycle boulevards in relation to arterials with bicycle lanes *(Blanc and Figliozzi, 2016)*.

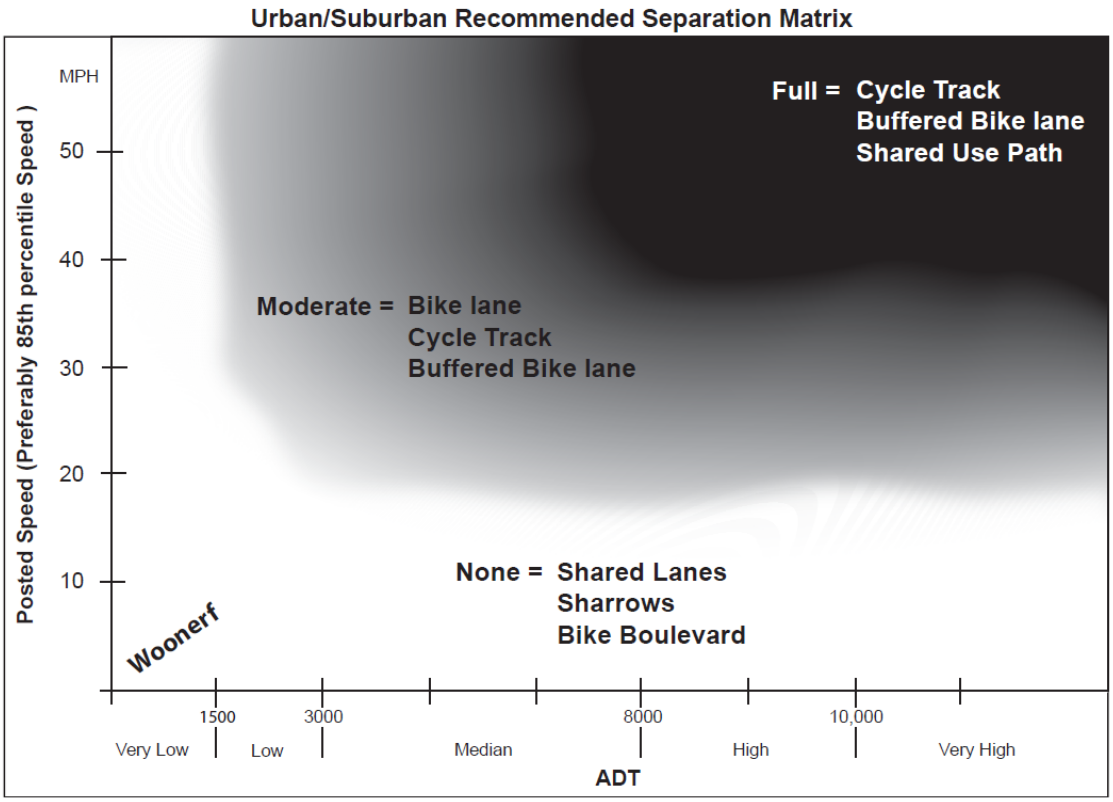

Figure 7.2: Bicycle Facility Separation matrix (Reproduced from Oregon Department of Transportation, 2011).

7.4 EXPANDED FUNCTIONAL CLASSIFICATION SYSTEM FOR HIGHWAYS AND STREETS

The NCHRP Report 855, *Expanded Functional Classification System for Highways and Streets (Stamatiadis et al., 2017)* provides a guideline for determining appropriate design criteria and elements of roads based on their context and type, expected functions, and users' needs.

In the *Expanded Functional Classification System for Highways and Streets* (Expanded FCS), five contexts are identified primarily by population density, land uses, and building setbacks as rural, rural town, suburban, urban, and urban core. Roadway types are proposed as interstates/freeways/expressways (guided by FHWA standards), principal arterials, minor arterials, collectors, and locals, and are based on their network function and connectivity between centers of activity. User groups are identified as drivers (of automobiles, transit and freight operators are handled separately), pedestrians, and bicyclists. Figure 5 shows the Expanded FCS conceptual user priority matrix.

The Expanded FCS provides design accommodation elements and ranges for combinations of context, roadway type, and user needs. Considerations are made for the efficiency of travel, route spacing, and volumes per travel mode. Additional factors for bicyclists and pedestrians include typical trip lengths and level of vulnerability to which the user is exposed. At a minimum, the design should accommodate intended users of concern or those users should be moved to a parallel route.

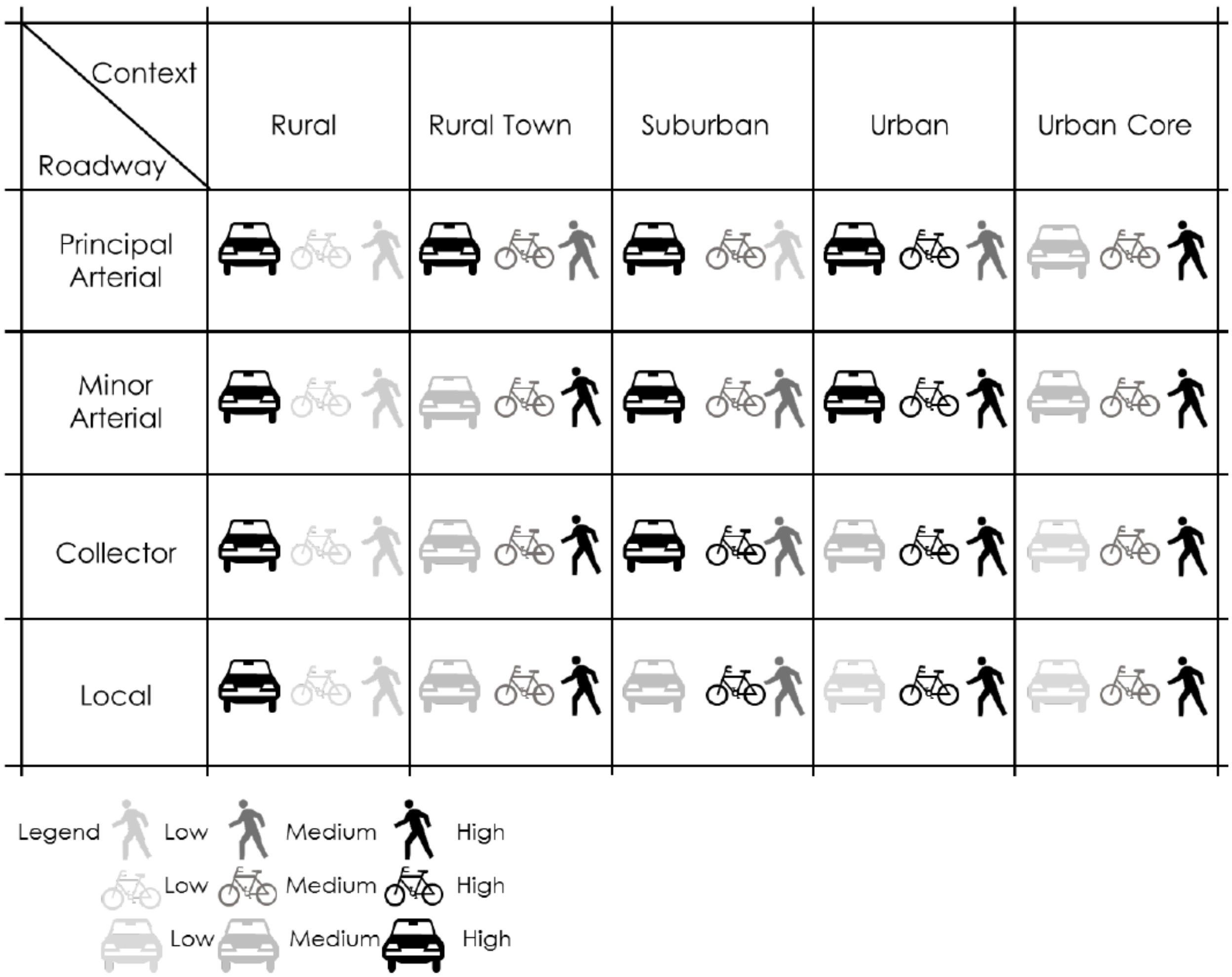

Figure 7.3: Expanded FCS conceptual user priority matrix (Reproduced from *Stamatiadis et al., 2017*).

Target operating speed and the balance between mobility and access define the context-roadway type interaction between drivers. Target operating speed is grouped as Low (<30 mph), Medium (30-45 mph), and High (>45 mph). The limits for each category are based on established practices and research. Speeds of 20 mph or less should be considered in areas of higher pedestrian activity in urban and urban core contexts as 20 mph is regarded as the survivability speed for pedestrians and bicyclists in the event of collision with a motor vehicle. Upper limits for high speed roads are based on the Green Book *(American Association of State Highway and Transportation Officials [AASHTO], 2011)*. Access is the frequency of driveways or intersections and based on distance between access points, categorized as Low (>0.75 mi), Medium (0.75-0.25 mi), and High (<0.25 mi). Mobility is qualitatively defined as congestion level and categorized as Low (congested conditions), Medium (some congestion), and High (free flow). Target operating speed and mobility typically decrease along the context continuum (rural to urban core) as well as roadway type (principal arterial to local) while the opposite is true for access.

Guidance for bicycle facilities is based on the level of separation necessary from motorized vehicles. The level of separation should be based on the speed of traffic, context, and roadway type as well as the amount of bicycle traffic on the facility. Higher vehicle speeds and volumes with higher bicyclist volumes generally indicate a need for increased separation.

Pedestrian facilities are categorized by their width as None, Minimum (as required by Americans with Disabilities Act), Wide, and Enhanced (provides additional space than Wide to accommodate congregating groups or street furniture). The width is determined by the anticipated or potential levels of pedestrian traffic. Separation from the travel way is also an important design consideration with medium and high-speed roadways typically requiring increased separation which might be in the form of a landscaped buffer, bicycle lanes, or parking areas.

A complete matrix relating the user needs and design considerations for each mode can be seen in Table 7.1.

Table 7.1: Expanded FCS Multimodal Matrix by Context and Roadway Type. (Reproduced from *Stamantiadis et al., 2017*)

ROADWAY	CONTEXT		
	Suburban	**Urban**	**Urban Core**
Principal Arterial	M/H speed M mobility M access	L/M speed M mobility M access	L speed M mobility M access
	LC: L separation NC: M separation CC: H separation	LC: L separation NC: M/H separation CC: H Separation	LC: L separation NC, CC: M separation
	P1: *; P2: Min; P3, P4: Wide	P2: Min; P3: Wide; P4: Enhanced	P3: Wide; P4: Enhanced
Minor Arterial	M speed M mobility M access	L/M speed M mobility M/H access	L speed M mobility M/H access
	LC: L separation NC: M separation CC: H separation	LC: L separation NC, CC: M separation	LC: L separation NC, CC: M separation
	P1: *; P2: Min; P3, P4: Wide	P2: Min; P3: Wide; P4: Enhanced	P3: Wide; P4: Enhanced
Collector	M speed M mobility H access	L speed M mobility H access	L speed M mobility H access
	LC: L separation NC, CC: M separation	LC: L separation NC, CC: M separation	LC, NC: L separation CC: M separation
	P1: *; P2: Min; P3, P4: Wide	P2: Min; P3: Wide; P4: Enhanced	P3: Wide; P4: Enhanced
Local	L speed L mobility H access	L speed L mobility H access	L speed L mobility H access
	LC, NC, CC: L separation	LC, NC, CC: L separation	LC, NC, CC: L separation
	P1: *; P2: Min; P3, P4: Wide	P2: Min; P3: Wide; P4: Enhanced	P3: Wide; P4: Enhanced

Speed, Mobility, Access, and Separation levels: H-high; M-medium; L-low.
Bicycle connectors: LC-Local; NC-neighborhood; CC-citywide.
Pedestrian traffic levels: P1-rare/occasional; P2-low; P3-medium; P4-high
Pedestrian facility width: *-site specific considerations; Min-minimum; Wide-greater than minimum; Enhanced-wide for large congregating pedestrian groups.
Pedestrian facility separation should be considered in conjunction with driver target speeds.

7.5 VISION ZERO

Vision Zero can be defined as a campaign to improve road safety for all users. Its goal is to eliminate all traffic fatalities among all road users in part through speed management *(Vision Zero Network, 2018)*. The approach to setting speed limits, according to a vulnerable road user's tolerance to impact force, is an example of an injury minimization method or safe system approach *(Forbes et al., 2012)*. Speeds no higher than 30 km/h (20 mph) are recommended to reduce pedestrian and/or bicyclist fatalities.

Vision Zero also shifts the emphasis from the "unsafe driver" to the "unsafe road" and also include automated enforcement strategies (such as speed cameras, red light cameras, etc) to complement improved road design elements. Vision Zero also focuses on "safer vehicles" and "alert/compliant road users" (drivers, pedestrians, cyclists).

As of January 2019, 44 cities in the US have committed to the Vision Zero goal of eliminating traffic fatalities within a designated time frame with a clear plan in place *(Vision Zero Network, 2018)*.

Reviews of the following cities' action plans or yearly reports revealed reducing speed limits citywide or in designated zones is a common goal:

- Chicago has a citywide speed limit of 30 mph unless otherwise posted. As part of the Milwaukee Avenue safety project, the speed limit was reduced to 20 mph along the Greenway corridor *(City of Chicago, 2017a; City of Chicago, 2017b)*

- Denver's action plan includes the goal to lower speed limits with a priority on arterials and to create 20 mph slow zones in areas of sensitive land use such as residential neighborhoods, school zones, and near high concentrations of senior citizens *(City of Denver, 2017)*.

- Los Angeles installed its first "Senior Slow Zone" which established a speed limit of 25 mph and plans to install 15 mph school safety zones within 500 feet of a school. The City also has a goal of completing all speed surveys over ten years old *(City of Los Angeles, 2018)* as this will enable radar or laser speed gun enforcement under California law. Due to California rules regarding setting speed limits at the 85th percentile speed and results from recently updated speed surveys, speed limits have been increased on approximately 100 miles of urban roadway, the majority by five mph *(Fonseca, 2018)*. The City of Los Angeles plans to explore more appropriate methods for setting urban speed limits where there are large numbers of vulnerable road users *(City of Los Angeles, 2018)*.

- New York City has lowered the citywide speed limit from 30 mph to 25 mph, created 25 new arterial slow zones by using a combination of lowered speed limits, signal timing changes, signage, and increased enforcement, and implemented eight new neighborhood slow zones with a speed limit of 20 mph *(New York City, 2018)*.

- Philadelphia has reduced the residential speed limit from 30 mph to 25 mph. The non-residential urban speed limit is 35 mph. Philadelphia also plans to develop neighborhood slow zones *(City of Philadelphia, 2017).*

- Portland's goals included improving street design in conjunction with reducing posted speed limits. In 2016 Portland received approval for an alternate method to set new speed limits on certain streets, placing greater emphasis on the safety of vulnerable street users *(PBOT, 2016)* and in 2018 Portland reduced the residential speed limit to 20 mph *(PBOT, 2019)*.

- Seattle lowered default citywide speed limits on all non-arterial streets from 25 mph to 20 mph and lowered speed limits from 30 mph to 25 mph on arterial streets (unless otherwise posted) in 2016. The City plans to review arterial speed limits in urban villages as they focus on lowering speeds *(Seattle Department of Transportation, 2017)*.

7.6 PORTLAND ALTERNATIVE SPEED ZONE PROCESS

Speed limits in Oregon are set under the authority of the Oregon Department of Transportation (ODOT). Current statutory speed limits in Oregon are given in Table 7.2 *(ORS 811.111)*.

Table 7.2: Statutory Speed Limits in Oregon.

Location	Speed (mph)	Details
Alley	15	
Narrow residential roadway	15	"Located in a residence district and not more than 18 feet wide at any point between two intersections or between an intersection and the end of the roadway"
Business district	20	Includes arterial streets. ORS 801.170 defines a business district as "the territory contiguous to a highway when 50 percent or more of the frontage thereon for a distance of 600 feet or more on one side, or 300 feet or more on both sides, is occupied by buildings used for business."
School zone	20	Must meet school zone requirements
Public park	25	
Residence district	25*	Excludes arterial streets. ORS 801.430 defines a residence district as "territory not comprising a business district that is contiguous to a highway that: (1) Has access to property occupied primarily by multifamily dwellings; or (2) Has an average of 150 feet or less between accesses or approaches to: (a) Dwellings, churches, public parks within cities or other residential service facilities; or (b) Dwellings and buildings used for business."
"Other"	55	
Interstate	65	

*The residential speed limit was reduced to 20 mph on April 1, 2018 in the City of Portland.

In order to change a speed limit, the Portland Bureau of Transportation (PBOT) must send a request to ODOT. The request and steps involved depend on the type of street and the desired speed limit. To help ease the request process and to support Vision Zero goals, PBOT was granted permission to use experimental alternate guidelines for setting speed limits on certain non-arterial, non-federally classed streets with current speed limits higher than 25 mph in 2016 *(Pappe, 2016; PBOT, 2019)*.

The alternative speed limit method considers the speed and proximity of vehicles to vulnerable road users the most important factor in determining a speed limit *(Batson, n.d.)*. Based on the graph in Figure 7.4 *(Wramborg, 2005)*, the Portland alternative method proposes ideal maximum speed limits based on achieving a 10% fatality risk. Under the alternative process, PBOT uses the following general guidelines when requesting new speed limits on eligible streets *(PBOT, 2019)*:

- 20 mph on shared space streets – where people walking, biking, scootering, and driving share the same space.
- 20 to 30 mph on streets with busy intersections & crash history, where sidewalks are unbuffered from driving lanes, or where bike lanes are immediately adjacent to driving lanes.
- 20 to 40 mph on streets without a median barrier or where there is no physical separation between people traveling in motor vehicles and people traveling outside of motor vehicles.

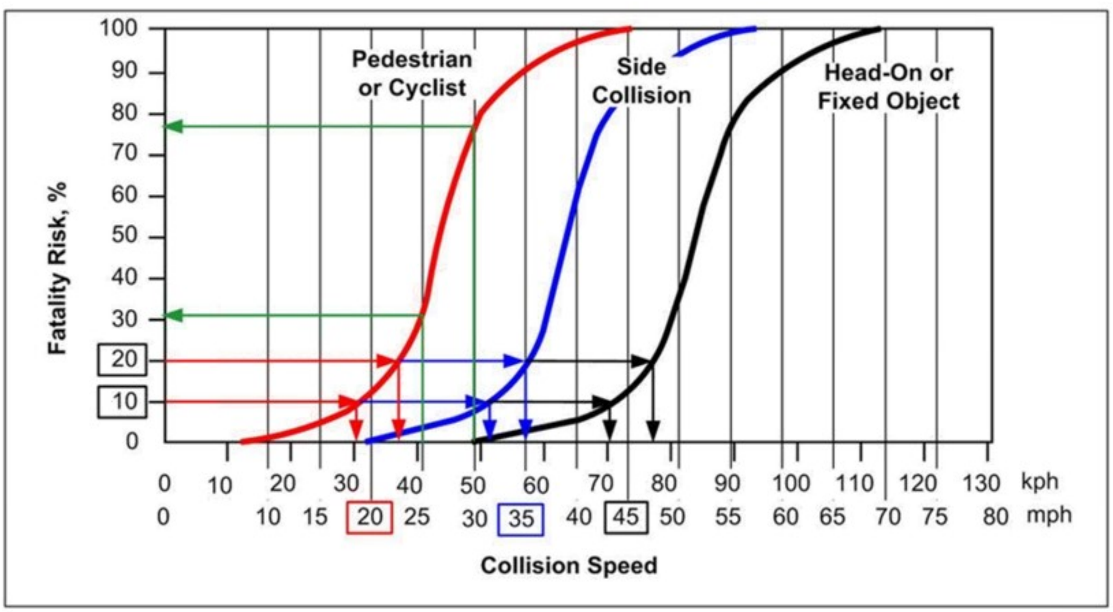

Figure 7.4: Fatality risk for three crash types as a function of vehicle speed. ***(Reproduced from Wramborg, 2005.)***

The guidelines listed above have been generalized from the simplified speed limit matrix seen in Figure 7.5 and are based on the road user types, street classifications, and roadway design features. In order to utilize the simplified speed limit matrix, the alternative methodology instructs data collectors to measure factors specific to pedestrian and bicycle infrastructure in addition to factors typical to more traditional automobile-focused approaches. The length of sidewalk and the length of bike lane present along a corridor as well as their separation from the closest edge of a motor vehicle lane should be measured. The typical width of a bike lane present along the corridor should also be measured *(Batson, n.d.)*.

Simplified speed limit matrix for fatal crash reduction by mode per OAR 734, Portland, Oregon

- Higher speed limits than indicated require mitigation measures from lower speed limits
- The lowest speed by mode controls; add mitigations for higher auto mobility
- Separation includes only space not regularly used for travel.

Street and limits:	**Street**								
Advisory		**Statutory**							
Speed	**10 mph**	**≤15**	**≤20**	**≤25**	**≤30**	**≤35**	**≤40**	**≤45**	**≤50**
PED	Shared roadway			5' sidewalk 100% one side	Sidewalk both sides; curb or swale; 8' separation	>8' separation both sides NCHRP 562 crossings: 20/Hr.	>12' separation both sides	Impermeable separation barrier	
BIKE	Shared roadway			≤ 5' bike lane	6' – 7' bike lane	Minimum 2' separation from autos	Permeable barrier	Impermeable separation barrier	
AUTO	Gravel roadway	≤ 9' travel lanes	10' travel lanes, greenway	10' travel lanes		≤ 11' travel lanes; Angle crash mitigations	Permeable center barrier; Roadside object setback or shielding		Impermeable center barrier
Notes:	None								

portlandoregon.gov
visionzeroportland.com

Figure 1.5: Portland simplified speed limit matrix. ***(Reproduced from Batson, n.d.)***

7.7 SUMMARY

The FHWA has developed a tool (USLIMITS2) to assist engineers and practitioners in selecting proper speed limits based on the type of road and site-specific characteristics. For developed areas, inputs required are the area type, the number of through lanes, driveways, and traffic signals, the presence of on-street parking, the extent of pedestrian and bicycle activity, and whether the section is one-way. Crash data for at least three years is also recommended. For road sections in developed areas, the recommended speed ranges from 20 to 50 mph.

Expert systems and algorithms, such as USLIMITS2 and SaCredSpeed, can guide engineers and practitioners to set reasonable speed limits and to detect credibility issues when operating speeds are higher than the posted speed limit.

Alternative design approaches, such as the *Institute of Transportation Engineers (2017)* report to implement context sensitive designs on multimodal roadways or the Expanded Functional Classification System for Highways and Streets, also provides guidance on speed limits, amount of separation required between motor-vehicle and bicycle traffic, and sidewalk widths based on the road context, the road classification, and the desired mobility and access of the road. The potential benefits and/or unintended consequences of these alternative approaches have not yet been thoroughly studied in the US.

With the proliferation of the Vision Zero campaigns, many communities are setting goals or taking actions toward lowering speed limits, especially in urban and residential areas where there are high numbers of active travelers. Several cities have recently lowered their default speed limit by five mph to 20 or 25 mph. By lowering speed limits, cities expect to improve traffic safety and reduce severe injury and fatality crashes.

As part of their Vision Zero Action Plan, Portland has developed an alternative methodology for setting speed limits that is based on a maximum fatality risk assessment of 10%. The risk is determined by the speed and proximity of adjacent motor vehicles to the most vulnerable road users, typically pedestrians and cyclists. The methodology guides engineers to set the speed limit to the lowest safe speed for the most vulnerable road user until greater protection can be provided for that user.

8.0 SUMMARY

The literature review indicates that posted speed limit increases tend to increase operating speeds and posted speed limit decreases tend to decrease operating speeds; however, there is a lot of variability around the mean observed effects. It is estimated that, on average, a 1 mph speed limit decrease is likely to result in a 0.25 mph decrease in the mean traffic speed *(OECD, 2006; Elvik 2012)*.

Speed limit compliance is not always easily achieved. A survey of drivers conducted by AAA Foundation for Traffic Safety found that nearly half of respondents (47.6%) reported driving 10 mph over the speed limit on a residential street at least once in the past 30 days with 12.9% indicating they engaged in the behavior fairly often or regularly *(AAA, 2018)*.

8.1 CURRENT SPEED ZONE GUIDELINES

Current US speed zone guidelines are predominantly based on statutory guidelines or by conducting an engineering study utilizing the 85th percentile of vehicles operating speeds and sometimes other factors. Current procedures are well established and widely utilized. Reviews of guidelines set forth by the FHWA and the states of California, Massachusetts, New York, and Oregon show adjustments as much as ten mph below the 85th percentile speed may be allowed. Adjustements are usually allowed for areas with higher than average crash rates attributed to speeding, geometric constraints, high driveway or access density, or a high potential for encountering an active traveler. Unlike guidelines from other jurisdictions, Oregon guidelines indicate that other factors such as pedestrian and bicycle movements, type and density of adjacent land use, enforcement, crash history, public testimony, traffic volumes, number of accesses will be consider in the engineering study.

When conducting an engineering study, the general consensus among states is to use spot speed data to calculate prevailing speed parameters. Laser and radar guns, pneumatic tubes, and on-road sensors are the most commonly used tools to collect speed data. Continuous speed data collection methods include radar guns connected to laptop computers and vehicle-based devices such as mobile phones and GPS units. Data collection guidelines predominantly recommend a minimum of 100 observations taken in ideal weather conditions during off-peak hours while avoiding times during weekends, holidays, or special events. Geometric, road, and roadside characteristics are often recorded by conducting site visits.

Setting the speed limit near the 85th percentile can improve compliance and reduce the burden of enforcement but the literature review indicates that there can also be unintended consequences. These unintended consequences can be summarized as follows:

a) Operating speeds may spiral up, e.g. increasing speed limits can increase operating speeds which in turn results in an increment of the 85th percentile of operating speeds,

b) Increases in speed limits can result in increases in crash frequency and crash severity along the modified speed zone, and

c) The 85th percentile of the operating speed does not directly account for the presence of active users and some jurisdictions do not mandate the analysis of additional factors.

8.2 SAFETY AND SPEED

The factors that affect operating speeds are usually confounded which hinder the estimation of individual impacts. Furthermore, the relationship between urban traffic and crashes is more complex in urban areas than in rural highways *(Cameron and Elvik, 2010)*. However, it is widely accepted that there is positive relationship, albeit a complex one, between speed and crash frequency; higher speed is positively correlated with higher crash frequency at a segment level. At a network or area wide level, the relationship between speed and crash frequency is likely to be more complex due to potential traffic diversion and speed spillover effects.

Regarding active users, there is evidence of a positively correlated relationship between speed and injury severity, although the magnitude and shape of such relationship may differ across studies. Unfortunately crash datasets do not report the actual speeds of motorized vehicles and active users at the time of a crash. However, based on the law of physics and the changes in kinetic energy when a crash between a motorized vehicle and a vulnerable user takes place, this relationship can be safely assumed to be a causal relationship.

There are many studies reporting crash changes in relation to changes in posted speed limits but the vast majority of the studies analyze motorized vehicle crashes. Extensive literature pertaining to the effects of speed limit changes on crashes involving active users in urban areas is lacking. More research is needed to better understand the effects of traffic speed management in relation to pedestrian safety and the effectiveness of new comprehensive safety programs like Vision Zero *(Sanders et al., 2019)*.

8.3 SPEED MANAGEMENT

In recent years there is a consensus in many countries towards thinking about speed limits not at a segment level or in isolation but rather as one component of a holistic speed management system. A speed management system should encompass not only posted speed limits at network or area level but also related aspects of the engineering design, traffic safety, enforcement, education, and emergency services. Speed management should be considered an ongoing and continuous endeavor that also requires interagency coordination *(OECD, 2006)*.

Roadway design can be utilized to affect operating speeds. Number of lanes as well as posted speed limit were commonly positively correlated with increased operating speeds while the presence of parking or sidewalks produced mixed results within the studies examined. Other characteristics examined in the reviewed research included lighting conditions; adjacent land use; the presence of medians, shoulders, or crosswalks; roadside object density; and segment length. Speed management tools also include traffic calming treatments which are typically applied to local or collector streets. Vertical treatments such as speed humps or raised crosswalks have been found effective at reducing motorized vehicles speeds and volumes. Lane width reductions, road diets, gateway treatments, and roundabouts or traffic circles are also common countermeasures.

The perceived credibility of speed limits, social influence, and personal biases were found to affect levels of support and speed limit compliance. Targeted social campaigns may help increase support and compliance when posted speed limits are reduced. Enforcement, including automated speed or red signal cameras, is another effective and common countermeasure.

Successful speed limit reductions often require simultaneous engineering design changes, educational campaigns, and increased enforcement. Successful interventions can be measured by the convergence of operational speeds towards design speed and speed limits. The convergence of operational speeds requires changes in both mean traffic speeds but speed variability. While speed limits are the most common method for managing speed *(NHTSA, 2014)*, the literature review indicates that speed limits alone are usually not sufficient to effectively control operating speeds *(NTSB, 2017; AAA, 2018; Kallberg et al., 1999)*.

8.4 DATA DRIVEN APPROACHES

Some crash studies do not take into account exposure. Many studies adjust crash data or crash severity utilizing vehicle volumes or vehicle miles traveled. Bicycle and pedestrian volumes are usually not included and therefore crash rates typically do not reflect the level of active user exposure.

Although it appears to be seldom utilized *(Fitzpatrick et al., 2019)*, the knowledge-based expert system USLIMITS2 can be used to select appropriate speed limits. A number of site-specific characteristics, speed and crash rate metrics, bicycle/pedestrian activity, AADT, and current statutory limits are required inputs. Three years of crash data are recommended. However, USLIMITS2 was not designed specifically for urban environments with a high percentage of active users. Outside the US, tools like SaCredSpeed are used to set credible speed limits by comparing roadway design and factors that affect speed limit credibility.

Better multimodal data and well-designed performance measures can provide an adequate framework to continuously monitor and improve roadway conditions for all users in a balanced manner.

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APPENDIX A

Author	Facility Type, Area Description	
	Independent Variables	
Dependent Variables	**Significant**	**Insignificant**
Allen-Munley et al. (2004)	Urban roads, New Jersey	
•Bicyclist injury severity	•Daylight hours •Population density •Grade* •Classified as highway •One-way road* •Pavement condition •Truck route •Motor vehicle volume per lane •Lane width* *Variables found significant at 95% confidence interval. All others at 90% confidence interval	•Posted speed limit •Household income •Median •Horizontal curve •Parking •Bus route •Crash occurred at signalized intersection •Residential zone •Weather condition •Victim was < age 16
Bar-Gera et al. (2017)	Non-urban roads, Israel	
•Difference in operating speed from before to after speed camera installation	•Months before or after camera installation •Distance from speed camera	

Author	**Facility Type, Area Description**	
	Independent Variables	
Dependent Variables	**Significant**	**Insignificant**
Bassani et al. (2016)	Urban arterial, Turin Italy	
Operating speed mean and deviation •All conditions (1) •Sunny (2s) •Cloudy (2c) •Nighttime (2n)	For mean speed: •Sky condition sunny/cloudy (1) •Mean illuminance (1, 2s, 2c) •Posted speed limit (all) •Lane position (all) •Left shoulder width (2s) For standard deviation: •Sky condition sunny/cloudy (1) •Mean illuminance (1, 2c, 2n) •Posted speed limit (all) •Lane position (all) •Number of carriageways (all) •Carriageway width (1, 2c) •Lane width (1, 2c) •Median width (2s, 2n) •Right shoulder width (1, 2n) •Left shoulder width (2s, 2c, 2n) •Ramp density (2s, 2c, 2n) •Driveway density (all) •Intersection density (1, 2c, 2n) •Sidewalks (2c, 2n) •Pedestrian crossing density (1, 2c, 2n) •Distance to nearest curve (2c, 2n) •Distance to furthest curve (2s, 2c, 2n) •Distance to nearest intersection (2s) •% road path where lane change forbidden (2c)	•Number of lanes per direction •Right shoulder presence •Left shoulder presence •Curvature •Presence of ramps •Presence of driveways •Presence of intersections •Presence of pedestrian crossing

Author	Facility Type, Area Description	
	Independent Variables	
Dependent Variables	**Significant**	**Insignificant**
Bassani et al. (2014)	Urban arterial and collector, Torino Italy	
•Operating speed central tendency •Operating speed dispersion	For central tendency: •Number of travelled ways •Lane position •Curvature For dispersion: •All geometric and operational variables found significant	•Posted speed limit •Travelled way width •Number of lanes per direction •Lane width •Median width •Ramps (for entering or exiting main travelled way) •Ramp density •Intersections •Intersection density •Pedestrian crossing density
Cameron & Elvik (2010)	Urban and rural roads of multiple classifications from many countries	
•Change in number of crashes •Change in number of injured persons or fatalities due to crashes	•Mean speed change	
Caviedes, Á. & Figliozzi, M. (2018, January)	ODOT highway network, neighborhood concepts D, E, F	
Crash severity/fatality risk for: •Pedestrians •Bicyclists	For both: •Location (segment/intersection) •Lighting •Alcohol intoxication •Vehicle movement (straight/turning) •Age For pedestrians only: •Weather condition •Vehicle type •Road classification •Road surface condition •Traffic control device •Posted speed limit	•Neighborhood concept •Season of year •Day of week •Time of day •Pedestrian/bicyclist location (crosswalk/roadway/midblock/bike lane) •Gender •AADT •AADT of trucks only •Number of lanes •Road width

Author	Facility Type, Area Description	
	Independent Variables	
Dependent Variables	Significant	Insignificant
Dinh & Kubota (2013a)	Urban residential streets, 30 km/h (20 mph) speed limit, Japan	
•85th percentile speed of tangent section (1) •Mean speed of tangent section (2) •85th percentile speed at intersection (3) •Mean speed at intersection (4)	•Length of street section (all) •Number of lanes (1) •Carriageway width (1, 2) •Right safety strip width (2) •Presence of sidewalk (1) •Roadside object density (1, 2) •Type of exiting intersection (4) •Distance from stop line of exiting intersection to nearest control point (3) •Distance from stop line to center point of exiting intersection (4) •Width of crossing street (4) •Crossing street/study street width ratio (3)	•Lane width •Roadway width •Left safety strip width •Sidewalk width •Driveway density •Street marking (centerline/edge line/none) •Land use development •Type of entering intersection •Distance from stop line to nearest pedestrian crossing strip of exiting intersection •Presence of pedestrian crossing strip at exiting intersection
Eluru et al. (2008)	Data sourced from the GES crash database	
•Non-motorist injury severity level	•Gender •Age* •Alcohol influence (non-motorist) •Alcohol influence (motorist) •Vehicle type •Speed limit* •Signalized intersection* •Time of day* •Snowy weather •Direction of impact *Variables were noted to have the most significant effects	All variables were significant

Author	**Facility Type, Area Description**	
	Independent Variables	
Dependent Variables	**Significant**	**Insignificant**
Eluru et al. (2013)	Urban local and arterial roads, Montreal Canada	
Vehicle operating speed: •Local roads •Arterial roads	For local only: •Number of lanes •Time of day •Number of sidewalks •Parking •One-way street •Bicycle route •Good pavement •Vertical grade > 10% For arterial only: •Time of day •Number of lanes •Speed limit •Weekday •Month	•Total width of street •Daily total traffic •Distance to next exit* •Distance from last exit* •Width of lanes* •Width per lane* •Vertical grade < 4%* •Horizontal curve* •Average width of lanes** •Presence of median** •Presence of parking** *Variables measured for local model only **Variables measured for arterial model only

Author	Facility Type, Area Description	
	Independent Variables	
Dependent Variables	Significant	Insignificant
Fitzpatrick et al. (2001)	Suburban, 4-lane arterial horizontal curve and tangent roads, Texas	
•Horizontal curve operating speed •Tangent operating speed	•Posted speed limit (significant in both models) For horizontal curve: •Deflection angle •Access density •Median type and width* •Roadside development (residential/commercial/park/school)* For tangent: •Lane width* *Variables only significant when excluding posted speed limit from the model	•Upstream control type •Downstream control type •Lane width – outside •Lane width - inside •Roadside environment (frequency/distance to rigid objects) •Pedestrian activity •Signal spacing •Curve radius* •Curve length* •Superelevation - outside* •Superelevation - inside* •Presence of curve or turn signs* •Presence of advisory speed sign* •Straight section length** •On-street parking** •Bike lane** *Variables measured for curve model only **Variables measured for tangent model only

Author	Facility Type, Area Description	
	Independent Variables	
Dependent Variables	**Significant**	**Insignificant**
Gargoum & El-Basyouny (2016)	Urban, two-lane roads, Edmonton Canada	
•Average speed •Collision frequency	For both: •Traffic volume •Segment length For average speed •Average vehicle length per location •Posted speed limit •Shoulders •Bus stop For collision frequency: •Average speed (as a mediator) •Standard deviation of speed •Horizontal curve •Median	•Percentage of speed limit violators •Bike lanes •Pedestrian crossing •Average temperature per location •Average wind speed per location •Average visibility per location

Author	Facility Type, Area Description	
	Independent Variables	
Dependent Variables	**Significant**	**Insignificant**
Gargoum et al. (2016)	Urban arterial and collector roads, Edmonton Canada	
Driver compliance to speed limit (difference between recorded speed and posted speed limit) •Collector •Arterial	For both: •Vehicle class (FHWA classification scheme) •Temperature •Wind speed •Season •Shoulder day (Monday/Friday) •Peak/Off-peak hours •Number of lanes •Vertical alignment •Posted speed limit •Land use For collector only: •Bus stop For arterial only: •Visibility •Median •Shoulder	•Horizontal alignment •Pedestrian crossing •Bike lane (not included in arterial model)
Gitleman et al. (2017b)	Non-urban, two-lane roads, 80 km/h (50 mph) typical speed limit, Israel	
Expected number of crashes: •Day hours •Night hours	Both models •Section length •Traffic volume •Mean speed •Road group parameter* *groups with higher frequency of secondary junctions, narrow shoulders or lanes, and more horizontal curves or grades were associated with higher numbers of crashes.	•Standard deviation of speed

Author	Facility Type, Area Description	
	Independent Variables	
Dependent Variables	**Significant**	**Insignificant**
Himes et al. (2013)	Urban and rural roads in Pennsylvania and Virginia	
•Mean speed •Speed deviation	For both: •Horizontal curve length •Grade % •Posted speed limit •Presence of left horizontal curve •Wooded adjacent land use For mean speed only: •Presence of vertical crest curve •Residential adjacent land use •Presence of at-grade rail crossing •Presence of median or turning lane For speed deviation only: •Unpaved shoulder width •Hourly traffic volume	•Tangent length •Vertical curve length •Number of access points per 305 m (1000 ft.) •Total shoulder width •Operating speed (for speed deviation) •Standard deviation of speed (for mean speed)

Author	Facility Type, Area Description	
	Independent Variables	
Dependent Variables	**Significant**	**Insignificant**
Islam & El Basyouny (2015)	Two-lane, urban residential collector roads in Edmonton, Canada	
Crash frequency •Univariate model PDO •Univariate model severe injury •Univariate model total •Multivariate model PDO •Multivariate model severe injury	For all: •Length of segment •AADT For univariate severe, multivariate severe and PDO: •Presence of a licensed premise •Stop controlled intersection density For univariate and multivariate severe: •Uncontrolled intersection density For univariate and multivariate PDO, univariate total: •Presence of street parking For univariate total and PDO: •Number of licensed premises within 400m •Presence of school zone For univariate total only: •Presence of access point	•Time period •Bus stop presence, number, density •Recreational center presence, number, density •School zone number, density •Senior center presence, number, density •Access point number, density •Road width •Presence of bike lane •Mid-block change •Presence of horizontal curve

Author	Facility Type, Area Description	
	Independent Variables	
Dependent Variables	**Significant**	**Insignificant**
Lee et al. (2017)	Variety of highways, depicted by photograph, Malaysia	
•Drivers' judged appropriate speed, compared to posted speed limit	•Road width •Presence of curve •Sight distance •Clarity of situation •Presence of lighting poles •Presence of intersections •Number of lanes	•View to the right (little/average/large) •View to the left (little/average/large) •Presence of buildings alongside road •Presence of trees to the right •Presence of trees to the left •Presence of vegetation to the right •Presence of vegetation to the left •Traffic on same carriageway •Traffic on opposite carriageway
Pei et al. (2012)	Road segments in Hong Kong	
Crash occurrence: •Distance exposure •Time exposure Crash severity: •Distance exposure •Time exposure	All models: •Average speed •Rainfall Crash occurrence, both: •Lane-change opportunity •Presence of central divider •Presence of bus stop •Day of week is Tuesday Crash severity, both: •Number of diverging ramps	•Standard deviation of speed •Curvature •Gradient •Number of merging ramps •Number of intersections •Presence of hard shoulder •Presence of on-street parking •Day of week other than Tuesday •Time of day period

Author	Facility Type, Area Description	
	Independent Variables	
Dependent Variables	Significant	Insignificant
Sadia et al. (2018)	Driving simulator	
Driver Level model •Average speed •Standard deviation of speed	For both: •Female gender •High driving frequency •Skills safety gap For average speed: •Age over 40 •Technical aversion •Risk awareness For standard deviation: •Law awareness	All variables were significant
Taylor et al. (2000)	Urban roads, Class A, B, C, Great Britain	
Crash frequency based on: •Average traffic speed and spread of speeds •Proportion of drivers exceeding speed limit and average amount over the speed limit	For both models: •Traffic flow •Number of pedestrians crossing road •Number of minor junctions •Road class (A, B, C) •Proportion of heavy goods vehicles •Location in London or not For average speed model only: •Average traffic speed •Spread of traffic speeds measure For proportion exceeding speed limit model: •Proportion of drivers exceeding speed limit •Average amount over the speed limit	All variables were significant

Author	**Facility Type, Area Description**	
Dependent Variables	**Independent Variables**	
Thiessen et al. (2017)	Urban, tangent collector and arterial segments, Edmonton, Canada	
Operating speed: •Combined •Arterial •Collector	All models: •Median width •Segment length •One-way road •Posted speed limit •Access density •Tree density •Average object offset •Average vehicle length Both arterial and collector models •Boulevard width •Pole density •Road width •Bus stop Combined model only •Type of sidewalk •Type of bike lane •Segment end treatment (geometry or intersection control) Collector model only •Roadside context •Service road	•Roadside hazard rating •Median type •Number of lanes •Parking •Tree maturity

Author	**Facility Type, Area Description**	
Dependent Variables	**Independent Variables**	
Wang et al. (2018)	Urban one-way arterial roads, Shanghai China	
Crash frequency	•Density of signal spacing •Number of lanes •Exposure (log-transformed VKT) •Mean speed •Speed variation •Time of day	•Segment length •Presence of medians •Presence of non-motorized lanes •Traffic volume