- FINAL -

Research Synthesis for AB 2363 Zero Traffic Fatalities Task Force

Prepared by

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Executive Summary

Transportation safety professionals strive to build a system on which no street user can be severally, or fatality, injured on. To accomplish such a safe system, it is necessary to effectively harness all the core protective opportunities provided by the system. For example, if we're looking at bicycle safety we would want alert and compliant cyclists and other road users, to make trips using safe bicycles and safe vehicles, on safe street design with adequate separation from motorized traffic, all of which are governed by safe speeds, and supported by effective cyclist protection and the medical emergency system when needed. While many of these protective components are discussed in the academic and professional literature, the topic of safe speeds has always the subject of much debate outside of professional circles too. At the heart of the debate is the intuitive trade-off between speed and safety. This synthesis includes a set of white papers that jointly provide a review of research on this topic, with an emphasis on speed limit setting practices and future opportunities to set safer speed limits and improve safety.

As part of this effort, the following findings have been established:

- **Evidence about speed and safety (why is this important?)**
  There is consistent evidence that as speed increases the probably of fatality given a crash increases too. This is supported by the laws of physics. There is also strong statistical relationship between average operating speed and crashes. This does not mean that traveling 50 mph on an urban arterial is safer than traveling 70 mph on a highway, but these findings establish that, all else equal, going faster is less safe. In light of this, reducing speed limits will most likely create safety benefits.

- **History of the 85th percentile (where does the current practice came from?)**
  The current practice of setting speed limits to the 85th percentile can be traced back to the late 1930s. This was based on the assumption that 85 percent of the drivers are sufficiently careful not to operate their cars too fast for conditions. It was also noted that it must, however, be adjusted in the light of crashes. There is no empirical study that demonstrates that the 85th percentile speed optimizes safety.

- **Limitations of the current speed limit setting practices (why we need to reconsider it?)**
  Drivers have a tendency to underestimate speed. This can range from an underestimate of 10% at higher speeds (70 mph) and up to 30% at lower speeds (35 mph). This demonstrates that drivers have limited capability to self-regulate a safe speed, especially at lower speed areas. It is therefore undesirable to rely on operating speed to establish safe speed. Moreover, over time, the practice of the 85th percentile can create an upward drift in operating speeds (*e.g., assume that collectively drivers elect speeds such that about half of them drive faster than the speed limit. This behavior, if coupled with a periodical application of the 85th percentile rule, would cause an upward drift in speeds*).

- **What are promising alternatives to set speed limits (how can we do it better?)**
  Other countries with desirable safety performance set speed limits based on the combination of the built environment including roadway features and geometry, the vehicle fleet, and a desire to establish credible speed limits to encourage compliance. Changes to the limit or to the layout of the road or environment are implemented to ensure alignment between credibility and desired safety.

Moreover, some jurisdictions, including domestic ones, are incorporating speed limit setting laws that give cities more flexibility to implement slower speed zones in urban areas.

- **Other opportunities to improve road user safety (what else can we do?)**
  There is a body of literature that can support practitioners in identifying a set of road design improvements to reduce crashes of all modes. The vehicle industry provides a high level of protection to occupants and is making initial efforts to provide more protection to non-occupants too. Infrastructure-based emerging technologies can provide safety benefits for all users.

Contents

1 Introduction

1.1 Kinetic energy and speed as a focal point to achieve vision zero and a safe system

By Offer Grembek

While the overarching objective of the transportation system is to provide mobility, transportation professionals dedicate significant resources to build a safe system. The aspirational objective is to establish a system on which no road user can suffer catastrophic outcomes. This is not only a moral imperative but also an economic one. The US road safety toll in 2016 claimed the lives of 34,439 people. Of those victims 23,714 were occupants or drivers of a motor vehicle, 5,987 were pedestrians and 4,738 are motorcyclists, bicyclists and other non-occupants. The estimated economic cost of all motor vehicle traffic crashes in the United States in 2010 was $242 billion, and is expected to be much higher today [1].

In the transportation safety realm, catastrophic outcomes are commonly considered fatal and severe crashes [2,3,4]. This is supported by initiatives by various national and international organizations [5,6,7,8], and by an increasing number endorsements of cities, states, and countries. [9]. These concepts represent a shift in the way we think about traffic safety by acknowledging that even compliant road users will misjudge road conditions. This, in turn, calls for a safe system that does not distinguish between road injury factors and can be conceptualized as a transport system that is inherently safe for human users [10].

The source of the energy absorbed by the road users during the crash is the kinetic energy carried by vehicles. When the transferred kinetic energy exceeds the human body's protective capacity, road users will get injured. The higher the amount of conveyed energy is, the severer the injuries may get. The car's impact kinetic energy can be calculated using the equation

$E = \frac{1}{2} m {v_1}^2$, Where:

E: The impact kinetic energy of the car (Unit: J).
m: The mass of the car (Unit: kg).
v_1: The impact speed of the car (Unit: m/s).

In this context, the problem reduces to a set of system components that should, in series or in parallel, dissipate or re-direct as much energy as possible before it reaches a road user. Ideally, the level of kinetic energy should be reduced such that the road user is not exposed to magnitudes that exceed what the human body can sustain. For illustration purposes, we consider an example of lane drifting by a distracted driver which would lead to a head-on collision with an oncoming vehicle. In this case, the components of the system need to provide enough buffers to protect the road users. These buffers can include brakes which can directly reduce the magnitude, a shoulder lane which can modify the crash angle and reduce the impact (a wide paved shoulder can also re-direct the energy so that the vehicles don't collide), followed by the vehicle's capability to absorb energy, and finally the occupant protection systems which help manage the eventual bodily impact. The expectation is that, jointly, these components would protect the road users from such perils that typically arise due to human misjudgment.

As noted, the reduction can be achieved by two methods. First, reduce the total impact kinetic energy that the vehicles possess. Second, make sure that the vehicle itself absorbs the kinetic energy as much as possible through crashworthy designs. During the pre-crash phase, only the first measure can be achieved as the collision does not occur throughout this time interval. Thus, the problem of protecting the road users can be converted to how to reduce the vehicle's kinetic energy to the maximum extent.

To accomplish such a safe system, it is necessary to effectively harness all the core protective opportunities provided by the system. For example, if we're looking at bicycle safety we would want alert and compliant cyclists and other road users, to make trips using safe bicycles and safe vehicles, on safe street design with adequate separation from motorized traffic, all of which are governed by safe speeds, and supported by effective cyclist protection and the medical emergency system when needed.

While many of these protective components are discussed in the academic and professional literature, the topic of safe speeds has always the subject of much debate outside of professional circles too. At the heart of the debate is the intuitive trade-off between speed and safety. On the one hand, we have physical and biomechanical principles that establish the fact that when we travel faster, we carry higher levels of kinetic energy which would need to be safely dissipated when something goes wrong. So, given the exact same circumstances going faster reduces safety. On the other hand, there is the claim that ultimate safety can only be obtained with zero mobility (aka no movement) so we should establish some criteria to determine what can be considered safe speed. This discussion transcends the academic realms since setting speed limits is a decision that is critical for operational, legislative, enforcement, and political matters.

In the US, the professional community has addressed this by adopting the practice of setting speed limits to the 85th percentile of the speed distribution. This synthesis includes a set of white papers that jointly provide a review of research on this topic, with an emphasis on speed limit setting practices and future opportunities to set safer speed limits and improve safety.

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2 Evidence about Speed and Safety

2.1 The impact of absolute speed on the risk of fatal injury

By Katherine Chen and Offer Grembek

Overview

Many variables affect injury severity in a motor vehicle collision, including the person, the vehicle, and the built environment. One widely studied variable is speed, specifically the relationship between the impact speed and the risk of fatality for vulnerable users. Pedestrians and bicyclists are particularly vulnerable due to the human biomechanical tolerance to force. Researchers around the world have studied speed and its impact on the risk of fatal and severe injuries using a variety of datasets, weights, and models. The following will describe some of these studies, including their conclusions and limitations.

Research Studies

Rosen et al (2010) conducted a literature search of analysis on pedestrian fatality risk as a function of impact speed and provided a summary of 11 highly relevant studies around the world. A summary of the findings is in *Figure 1*. The sample sizes were relatively small with considerable deviation in fatality rate from the national fatality rate. Five of the studies used relatively old datasets from before 1980. Nine of the studies did not adjust for bias and seven used European datasets. Rosen et al concluded that only two studies (Davis, 2001 and Rosen & Sanders, 2009) were methodologically robust.

Figure 1: Summary of the most relevant articles (Rosen et al 2010)

Table 1
Summary of the most relevant articles and their corresponding data sources.

	Data source	Sample size	Fatality rate	National fatality rate	Adjusted for bias	No. of pedestrians in the ages 0–14 years, 15–59 years, 60+ years	Section of this article
Ashton (1980)	Birmingham/Worcestershire, in-depth on-the-scene, 1965–1979, UK.	358	23%	3.5%	No	155, 121, 82	3.1
Pasanen (1992)	Birmingham/Worcestershire, in-depth on-the-scene, 1965–1979, UK.	358	23%	3.5%	No	155, 121, 82	3.1
Davis (2001)	Birmingham/Worcestershire, in-depth on-the-scene, 1965–1979, UK.	358	23%	3.5%	Yes	155, 121, 82	3.1
Cuerden et al. (2007)	OTS, in-depth on-the-scene, 2000–2007, UK.	108	6.5%	2.4%	No	–	3.1
Anderson et al. (1997)	Zürich, Police and medical data, 1978, Switzerland.	56	11%	5%[a]	No	–	3.2
Yaksich (1964)	St. Petersburg, Florida, Police data, 1958–1963, USA.	498	10%	–	No	120, 120, 258[b]	3.3
Hannawald and Kauer (2004)	MUH/GIDAS, in-depth on-the-scene, 1991–2003, Germany.	712	5%	2.2%	No	–	3.4
Rosén and Sander (2009)	GIDAS, in-depth on-the-scene, 1999–2007, Germany.	490	7%	2.2%	Yes	0, 328, 162	3.4
Oh et al. (2008a)	In-depth on-the-scene, 2003–2005, Korea.	182	30%	5%	No	–	3.5
Oh et al. (2008b)	In-depth on-the-scene, 2004–2005, Korea.	101	~30%	5%	No	–	3.5
Kong and Yang (2010)	In-depth on-the-scene, 2003–2009, China.	104	11%	–	–	–	3.6

Based on the national database STATS19 (Cuerden, private communication 2010).
[a] Estimate refers to Zürich 1978 (Walz et al., 1983).
[b] Estimated from Table 2 of Yaksich (1964).

Ashton (1980), Pasanen (1992), and Davis (2001) used the Birmingham data. Ashton concluded that the data was biased towards more severe injuries and fatalities. Rosen et al created a curve in Figure 2a based on the empirical fatality rates of the sample by Ashton (1980). Pasanen (1992) fit a regression model to understand pedestrian fatality as a function of impact speed. Davis (2001) weighted the proportion of fatal, severe, and slight crashes and adjusted it to the corresponding national proportions in the UK. Davis then applied an ordered logit regression and separated the data by age group. Davis found lower risk that Pasanen for the 0-14 and 15-59 age groups and a comparable curve for those age 60+. However, neither Pasanen nor Davis had access to the exact impact speeds so conducted analyses using aggregate figures. Davis included an assumption that impact speeds were uniformly distributed within each impact speed group (0-10 km/h, 11-20 km/h, […], 61-70 km/h, 71+km/h). This assumption potentially flattened the risk curve.

Cuerden et al (2007) analyzed data from the On The Spot (OTS) project that conducts traffic accident investigations from the Thames Valley and Nottinghamshire. The curve developed by Cuerden was similar to that of Davis (2001). Cuerden's work is considered high quality analysis but there are limitations to the reliability of the dataset because 59% of the sample have impact speeds imputed based on some physical evidence or subjective opinion.

Anderson et al (1997) used a small Zurich dataset biased towards an older demographic and towards more severe injuries. The risk curve developed was very steep from 46-55 km/h with risk ranging from 60-100% although the empirical risk was only 20% because the impact speed in the sample maxed out at 55km/h. Anderson acknowledges the data limitations but did not have alternate data to include.

Yaksich (1964) studied fatality risk as a function of travel speed, or posted maximum travel speed, using an American dataset selected to oversample the elderly. Yaksich did not derive a fatality risk curve, but instead identifies a risk based on speed limits. Rosen et al (2010) found that the pedestrian risk curve cited by Teichgraber (1983) likely references back to a report by Yaksich (1964).

Hannawald and Kauer (2004) analyzed fatality risk by estimating the potential effectiveness of a brake assist system and applied a logistic regression to the data to derive a curve estimating the risk of sustaining a maximum AIS5+ injury as a function of car impact speed. They then claimed this risk resembled a pedestrian fatality risk curve.

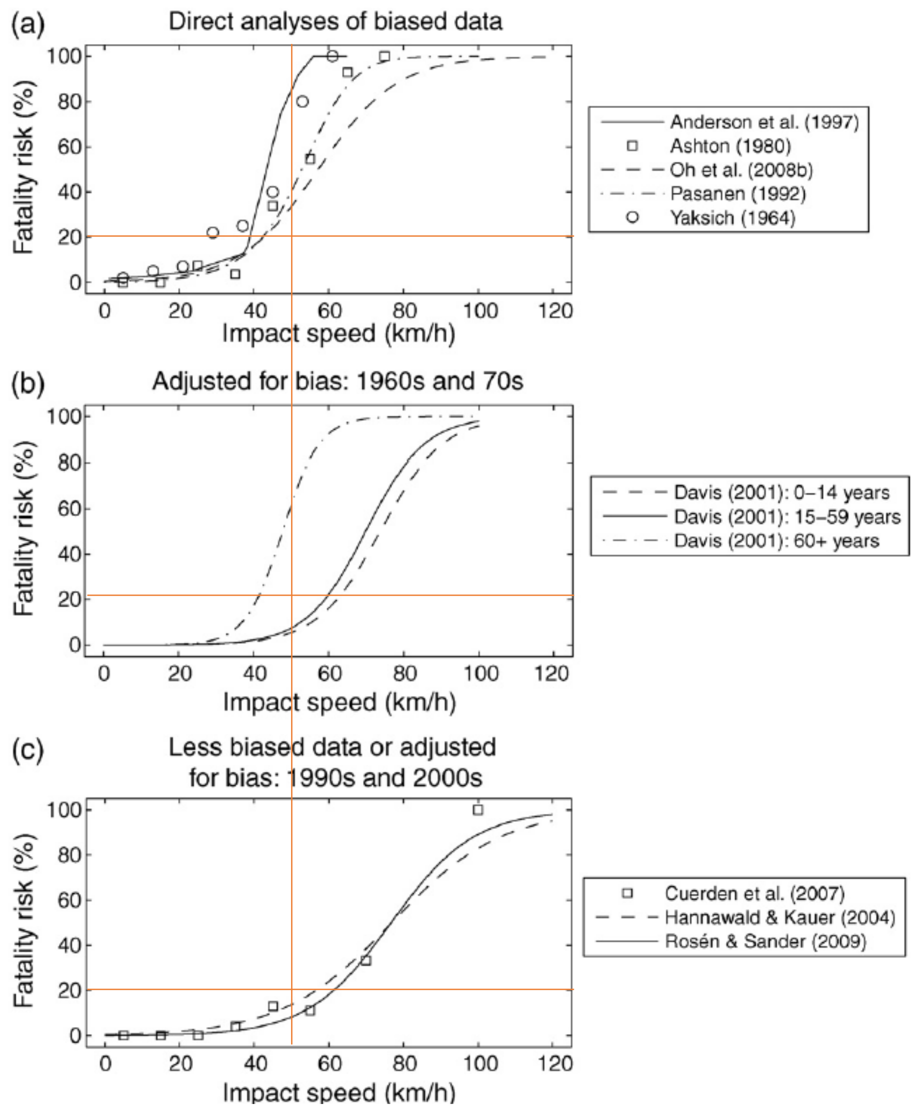
Rosen and Sander (2009) studied a subset of the data sample used by Hannawald and Kauer looking at only injured pedestrian age 15 and older struck by the front of a passenger car. Rosen and Sander developed a risk curve by logistic regression with a 95% confidence interval. However, their data was very sparse at speeds greater than 55km/h so the 95% confidence band is quite wide.

Oh et al (2008) used a Korean sample biased towards fatal crashes and performed logistic regression analysis using impact speed, pedestrian age, and vehicle types as explanatory variables. The risk curve shows high fatality risks even at moderate impact speeds.

Kong and Yang (2010) weighted a Chinese sample to derive fatality risk curves that showed higher fatality risk than the unweighted data. Rosen et al did not include this curve in *Figure 2* because of the questionable fatality rate reported in the data.

In summary, Rosen et al (2010) consolidated the findings from these studies together graphically of fatality risk as a function of impact speed for pedestrian struck by the front of a passenger car as seen in *Figure 2*. The risk curves developed show vastly different rates of fatality risk at an impact speed of 50 km/h. Each study can be refuted by the limitations of the dataset and/or analysis. Furthermore, fatality risk is a byproduct of medical treatment (Rosen et al, 2010) and pedestrian age (Henary et al, 2006).

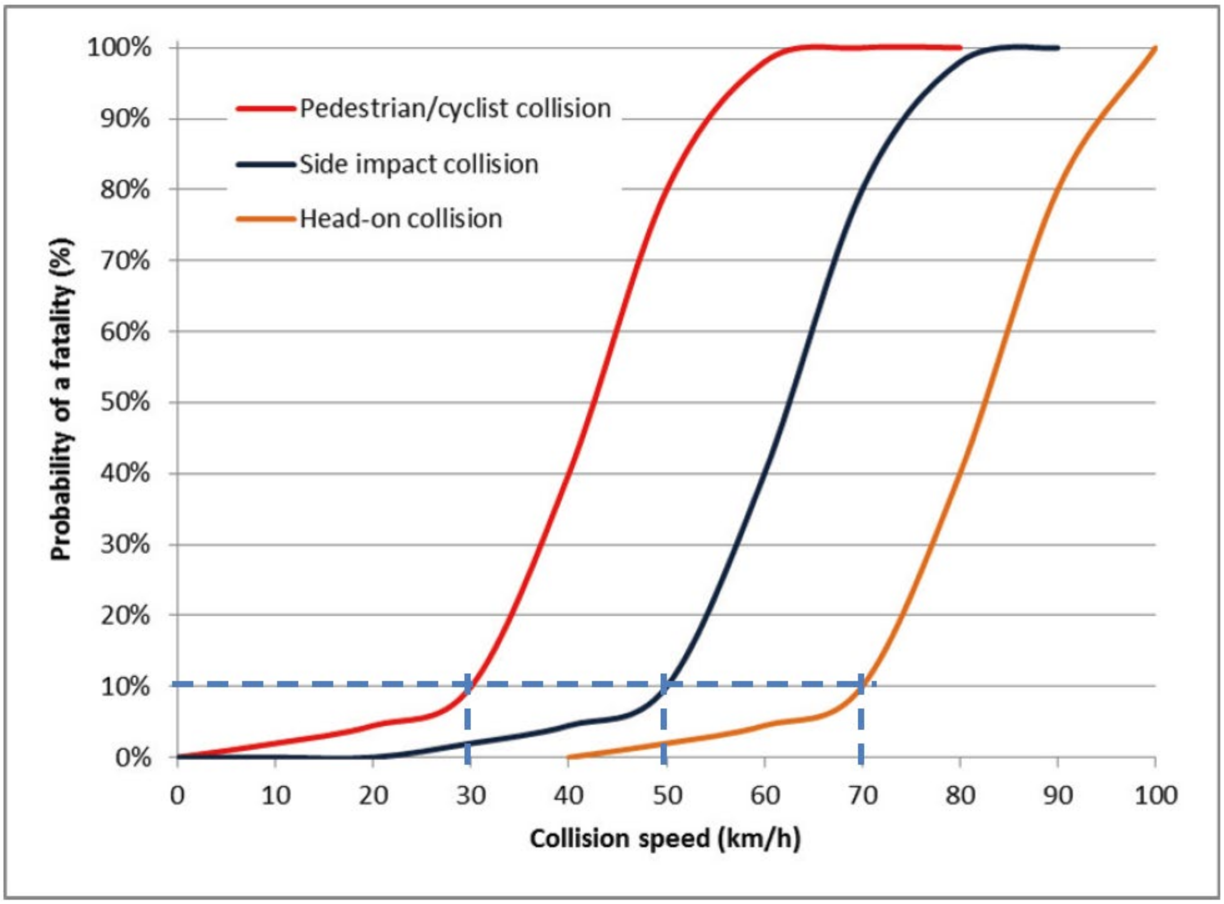
Figure 2: Pedestrian fatality risk as a function of impact speed by the front of a passenger car



The orange lines were added to denote an impact speed of approximately 50 km/h and a fatality risk of 20% across all graphs.

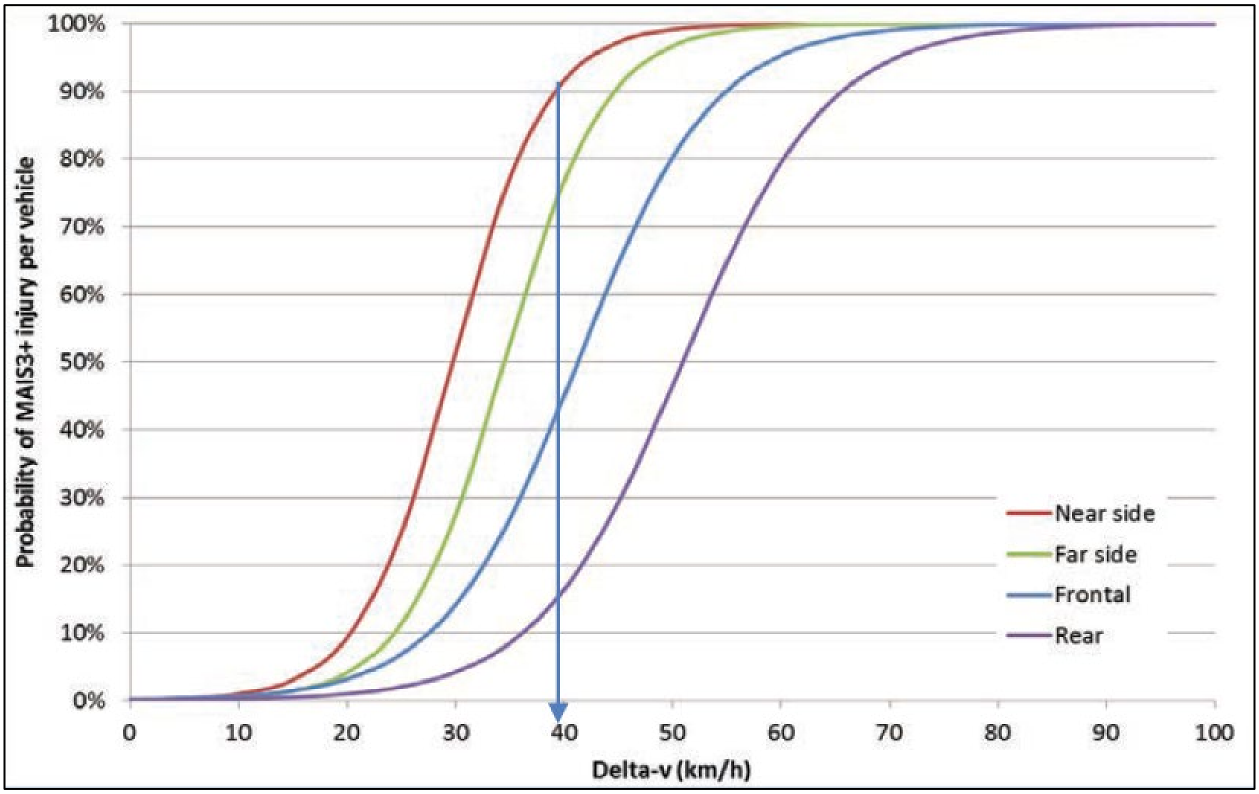
New Zealand and Australia adopted a model by Wramborg (2005) that shows the effect of impact speeds on fatality of selected crash types as seen in *Figure 3*. Wramborg's work shows that the probability of a fatality in a pedestrian/cyclist collision is considerably higher at lower speeds than that of vehicle-vehicle collisions. Specifically, it points out that there is a 10% chance of a fatal outcome at 30 km/h in a pedestrian/cyclist collision, at 50 km/h in a side impact collision, and at 70 km/h in a head-on collision. While this is often cited and used in policy development, Wramborg's conference paper does not provide research references or sources of information for the impact speed curves.

Figure 3: Wramborg's model for fatality probability vs vehicle collision speed



Unlike previous work on fatality risk, Bahouth et al (2014) used a binary logistic regression model to analyze the relationship between delta-v and the probability of a MAIS3+ (severe) injury for a front seat occupant in a vehicle. The curves in *Figure 4* assume seatbelt use, no rollover or secondary impact, and occupant ages between 16 and 55. Bahouth provided results based on individual vehicles in specific impact types rather than on crash events, e.g., two vehicles and two impact types. For vehicle-vehicle collision, Bahouth concluded that near side impact was the most severe of the occupants and rear impact is the least severe collision type.

Figure 4: Probability of severe injury of front seat occupants vs. delta-v of a vehicle in a crash (Bahouth et al, 2014)



However, researchers were interested in studying the relationship between delta-v and the road infrastructure to further the Safe Streets discussion. Tolouei et al (2011) derived the relationship between delta-v and vehicle masses, impact speeds, and the angle between their paths. This equation helps road agencies improve the design of infrastructure elements.

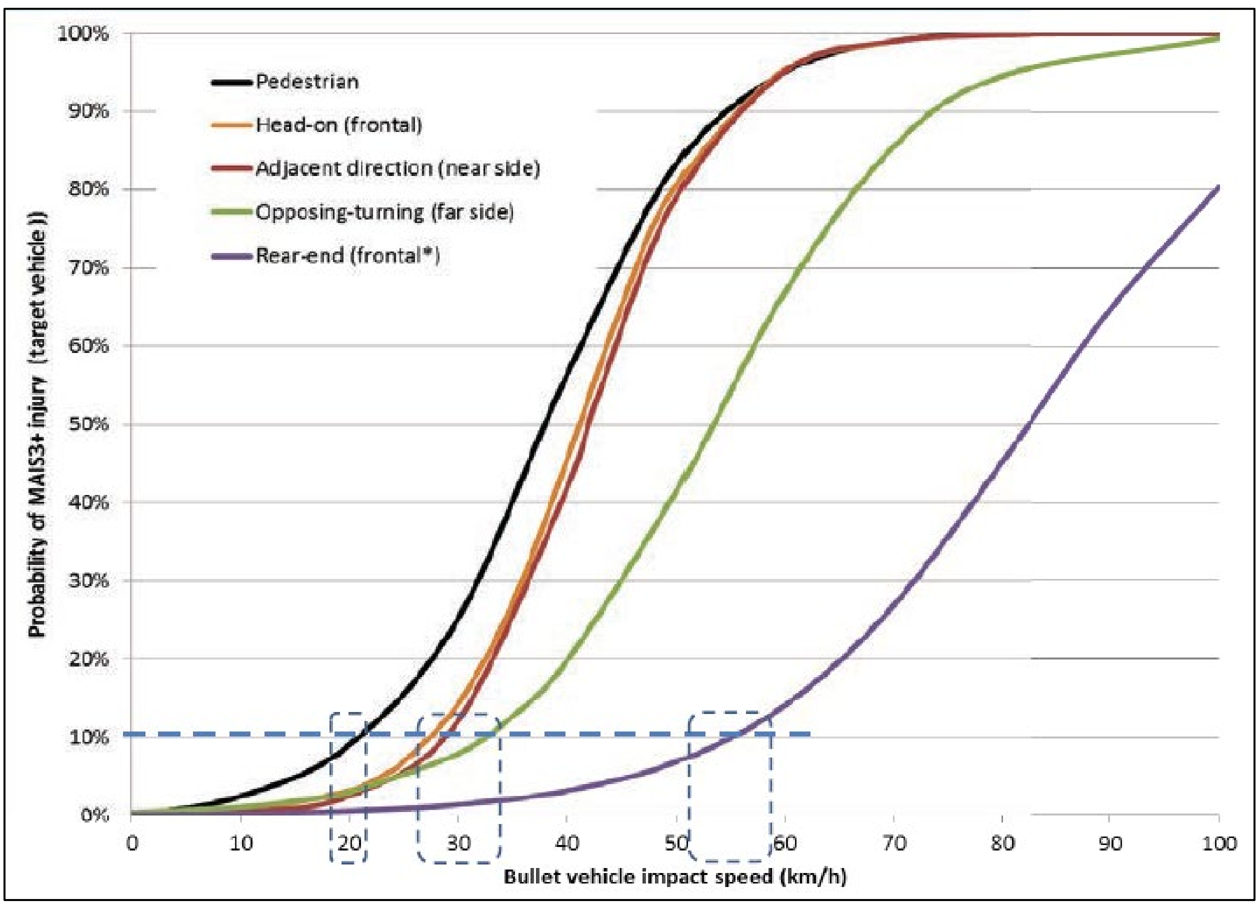
$$\Delta V = \frac{m_1}{m_1+m_2}\sqrt{V_1^2 + V_2^2 - 2V_1V_2\cos\phi}$$

Where, ΔV is vehicle change in speed due to the crash;
m_1 and m_2 are respective masses of the “bullet” and “target” vehicles;
V_1 and V_2 are their impact speeds; and
ϕ is the angle between the axis of travel of both vehicles.

Jurewicz et al (2016) calculated the probability of severe injury (MAIS3+) for each crash type using the assumed impact speeds, angles, and delta-v relationships from using the same assumptions as Bahouth (2014) in *Figure 4* to develop the vehicle-vehicle collision severe injury risk curves. For the vehicle-pedestrian crash, Davis (2001) was selected based on its methodology and relevance to this study. The pedestrian severe injury risk curve is based on updated empirical data from Davis (2001) at different impact speeds. Together the five curves combined are in *Figure 5*. Pedestrian collisions are at the highest risk of severe injury at all impact speeds followed by head-on, near-side, far-side, and rear-end collisions respectively.

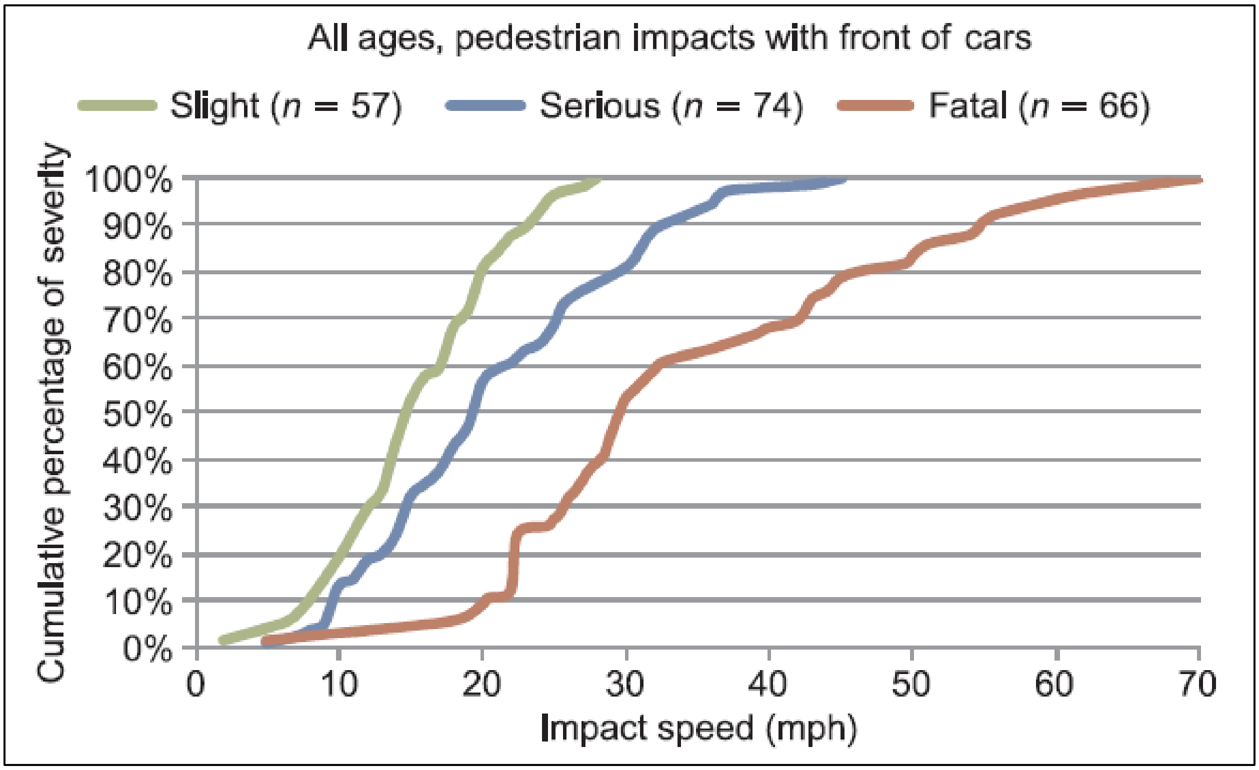
The impact speed curves developed by Jurewicz (2016) show a distinctly different relationship that proposed by Wramborg (2005) and Bahouth (2014). The greatest difference is seen for frontal head-on collisions. Where Wramborg found head-on to be the most forgiving impact type for fatalities with impact speeds up to 70 km/h for a 10% chance of death and Bahouth found it to be the second most forgiving for severe injuries, Jurewicz found it to be the highest risk impact type in vehicle-vehicle collisions. Jurewicz acknowledges that the curves are conceptually broad and that there are many assumptions and limitations to the model. Jurewicz curves justifiably question whether road infrastructure improvements to angles and impact speeds are sufficient under a Safe Systems approach of reducing fatality and severe injury. Ultimately, it is unclear which of the three sets of curves is most appropriate as high-level guidance for infrastructure design improvements but there are distinct similarities between them.

Figure 5: Model of severe injury probability vs bullet vehicle impact speed in different crash types, Jurewicz et al (2016)



Richards (2010) suggests that there has been a decrease in the risk of pedestrian fatality for impact speeds of 30+ mph due to improvements in car design and advancements in medical care. Richards analyzed the Ashton, OTS, and Rosen and Sander datasets to conclude that the risk of pedestrian fatality is similar for children and adults but higher for the elderly. Richards makes further astute observations that while the absolute risk of pedestrian fatality may be relatively low at 30mph, approximately half of all pedestrian collisions occur at these speeds as seen in *Figure 6*. This is significant, especially within a Safe Systems framework.

Figure 6: Cumulative impact speed for pedestrian casualties in the OTS and police fatal file dataset (Richards, 2010)



Tefft (2011) conducted a separate analyses using data from the NHTSA's National Automotive Sampling System (NASS) Pedestrian Crash Data Study. Tefft was interested in the risk of severe injury or death in relation to impact speed for pedestrians struck by a forward-moving vehicle (passenger car, SUV, pickup truck). In this study, death was defined as within 30 days of the crash as a result of injuries sustained in the crash. Tefft fitted a multivariable logistic regression model to the weighted, imputed data to estimate risk of severe injury and death relative to impact speed. Tefft's model for fatality and severe injury included: impact speed, age, age squared, height, weight, BMI, number of BMI units above 25, number of BMI units above 30, and type of striking vehicle. Similar to other studies, Tefft found that the data was biased towards fatal and severe injuries and that the majority of pedestrians were struck at relatively low speeds. Tefft's risk of severe injury and fatality curves increased linearly for impact speeds between 30mph and 50mph as seen in *Figure 7*. Furthermore, Tefft's curve for fatality was similar to that of Rosen & Sanders (2009). Tefft found that risks of severe injury or death are higher with light struck than by cars, and that risks are higher for older pedestrians as seen in *Figure 8*.

Figures 7 & 8: Risk of severe injury and death in relation to impact speed (Tefft, 2011)

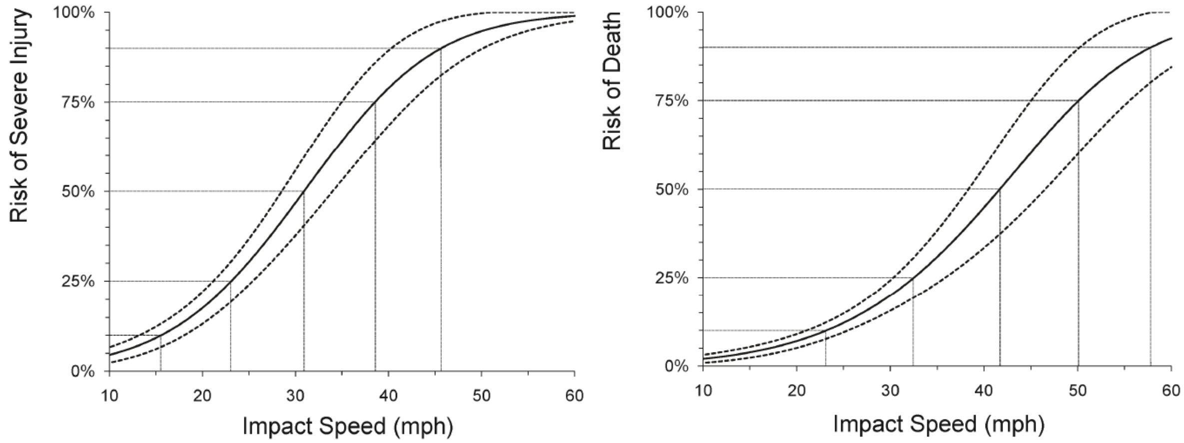


Figure 1. Risk of severe injury (left) and death (right) in relation to impact speed in a sample of 422 pedestrians aged 15+ years struck by a single forward-moving car or light truck model year 1989–1999, United States, 1994–1998. Risks are adjusted for pedestrian age, height, weight, body mass index, and type of striking vehicle, and standardized to the distribution of pedestrian age and type of striking vehicle for pedestrians struck in the United States in years 2007–2009. Dotted lines represent point-wise 95% confidence intervals. Serious injury is defined as AIS score of 4 or greater and includes death irrespective of AIS score.

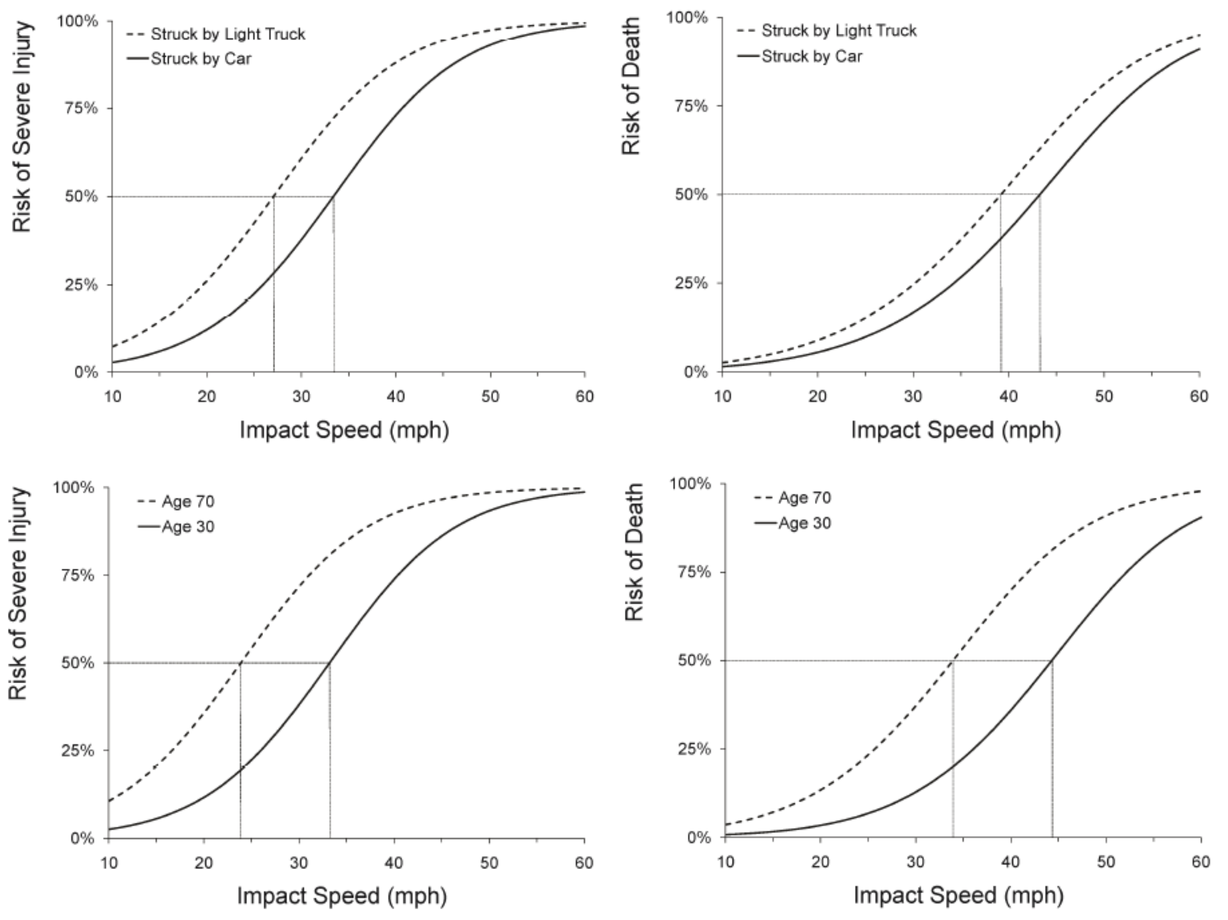


Figure 2. Risk of severe injury (left) and death (right) in relation to impact speed in a sample of 422 pedestrians aged 15+ years struck by a single forward-moving car or light truck model year 1989–1999, United States, 1994–1998. Risks are adjusted for pedestrian age, height, weight, body mass index, and type of striking vehicle. Top panel shows average risk for pedestrians struck by cars vs. light trucks, standardized to the age distribution of pedestrians struck in the United States in years 2007–2009. Bottom panel shows average risk for pedestrians ages 30 vs. 70, standardized to the distribution of type of striking vehicle for pedestrians struck in the United States in years 2007–2009. Serious injury is defined as AIS score of 4 or greater and includes death irrespective of AIS score.

Conclusion

Safe Systems policy and planning must address impact speeds with regard to human tolerance and ability to survive. While the studies range in terms of what the absolute risk of impact speed is, there is generally consensus that pedestrian fatality gradually increases with speeds up to 30 km/h before increasing much more rapidly in an S-shaped curve where overall fatality and/or severe injury risk increases with impact speed. At very low impact speeds, most pedestrians struck do not suffer a severe injury or fatality, but as impact speeds approach typical urban speed limits, the risk of injury increases exponentially per mile or kilometer increase. Several studies also reference other types of crashes and vehicle types as they relate to absolute risk. However, no study has proposed a different shape to the curve nor that higher speeds are safer.

Within a Safe Systems framework, it will be important to expand these studies to include more severe injuries' analyses. Many of these studies also rely on relatively old datasets, over 20 years old, and updated data analyses are important for understanding how these curves have changed. Over time, we expect to see all the curves shift to the right as medical advancements improve survivability and vehicle technology increase speed while reducing the risk of fatal and severe injuries. While there is no single curve agreed upon as the absolute risk of fatality or severe injury per impact speed, pedestrian survivability worsens as speeds increase. It will be critical for transportation professionals to account for the most vulnerable road users when designing roadways and setting speed limits.

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2.2 A review of speed limit effects on traffic safety

By Dillon Fitch, Sonia Anthoine, Bingchu Chen, Salvador Grover

Introduction and review process

In the following review we synthesize findings from primary and secondary research on the relationship between vehicle speed (i.e. speed of cars, trucks, and other motor vehicles but excluding speed of bikes and small vehicles lacking licensing requirements) and traffic safety with a specific focus on the role of speed limits in moderating this relationship. We break up the literature by two key road environments: (1) limited access roads (highways, freeways) where pedestrians and bicyclists are forbidden, and (2) all other roads that have mixed travel modes. Rural highways are a particularly unique in this classification because they tend to operate like limited access roads, yet they allow walking and bicycling. We classified studies conducted on rural highways as limited access if they only covered the safety of car drivers, and as mixed travel modes if they included safety of pedestrians and bicyclists.

Recent literature reviews and meta-analyses (Aarts and Van Schagen, 2006; Elvik et al., 2019; Wang et al., 2013) were particularly valuable in this synthesis. Many of the primary sources we reviewed came from bibliographic references from these reviews, along with traditional literature database searches. Of the sources we reviewed, studies with methodologies that indicated a higher level of internal validity were assigned more importance and thus their results weigh stronger on our qualitative synthesis. We gave before-and-after studies the most weight for their high validity in assessing the effect of a speed limit change (e.g. the speed limit change interventions reviewed by Elvik (2019).

We gave less weight to observational studies than before-and-after studies because of the inability to make causal inferences about the relationship between speed and safety. Within observational studies we gave more weight to studies with larger sample sizes and longer time series. Although inferences from observational studies are only associative (and not causal), in some cases they are still the best evidence for certain research questions. For example, in some before-and-after studies, speed limits are changed together with other variables (infrastructure and enforcement) making it challenging to determine the independent effect of each. Observational studies on the other hand tend to include speed limits as independent variables in multivariable regression models which estimate the conditional association between speed limit and key outcomes (e.g. vehicle speed and traffic safety).

Theory connecting motor vehicle speeds and safety outcomes

Vehicle speed has a basic physical connection to traffic safety. By Newtonian equations, the kinetic energy generated from a vehicle rises non-linearly with increasing speed. The greater the kinetic energy of a vehicle, the greater potential energy transfer to another person, vehicle, or object. This transfer of energy during a collision is the root cause of all traffic injuries and fatalities.

Vehicle speed also has behavioral connections to traffic safety. With increasing driving speed, driver vision the amount of visual information drivers must process increases per unit distance (Jo et al., 2014; Rogé et al., 2004). This has numerous cognitive and behavioral effects on drivers that are nearly universally negative. For example, faster speeds require greater distances to stop vehicles (Anderson et al., 1997; Elvik, 2012) and cause more driver fatigue and stress which can in turn have negative feedbacks on attention and cognitive function (Jo et al., 2014).

Because complex human behavior is involved in all traffic injuries, researchers are only roughly motivated by physical models and instead rely on empirical models to connect traffic speed to safety. A commonly used model to predict the relationship between mean vehicle speed and crash rate and severity is the Power Model (and the related exponential model). Originally proposed by Nilsson (2004), the model suggests that the number of fatal crashes, serious injury crashes, and all reported injury crashes change proportional to powers of the relative change in the mean speed of traffic. The base injury crash equation is based on the Newtonian equation for kinetic energy but the powers proposed for fatal crashes and serious injury crashes were originally based on best fitting values to data from Sweden (Elvik et al., 2004).

Most other empirical models are not motivated from physical equations but instead are formed from generalized statistical models designed to describe data generating processes that closely mirror the process for measuring crashes, injuries, and fatalities. Because this data is most commonly quantified by counts within classes (e.g. number of fatalities, number of minor injuries, number of crashes), generalized linear regression in the form of Gaussian, Poisson, and Binomial distributions are most common.

Motor vehicle speeds as a determinant of crashes, injuries, and fatalities

The relationship between vehicle speed and frequency of crashes is found to be positive in most studies (Elvik et al., 2019; Kloeden et al., 2001, 1997), but some studies find negative or negligible relationships (Baruya, 1998; Garber and Gadiraju, 1989). Because traffic crashes are determined by multiple factors, many of which likely interact in complex ways, in some cases speed reductions may result in more crashes. However, most of the evidence suggests the opposite, and explanations for how slower traffic might cause fewer crashes are rare. Some evidence suggests that the studies that find negative relationships between speed and crash frequency may be caused by poor methodological choices (e.g. model selection, data processing) (Imprialou et al., 2016; Wang et al., 2013). Given the conflicting evidence it is difficult to put a range on the effect of traffic speed on crash frequency. Taylor et al., (2000) find that for every one mile per hour reduction in average speed, crash frequency decreases by 2-7%. Other studies suggest that the rate of crash reduction depends on the absolute speed (i.e. a one mile per hour reduction from 70 mph will differ from a one mph reduction from 25 mph), and that at speeds around 20 mph, crash frequency could decrease by around 12% for a one mile per hour reduction of speed (Elvik et al., 2004).

Most peer-reviewed studies indicate that injury severity increases with vehicle speed (independent of road context) (Clarke et al., 2010; Hauer, 2009; Kaplan et al., 2014; O'Donnell and Connor, 1996; Shankar et al., 1996). Reducing speeds has a much stronger effect on reducing fatal crashes than it does crashes in general. Furthermore, as speeds decline so do injuries sustained from crashes. One meta-analysis suggests that the range of effects are a 7-22% reduction in fatal crashes with a one mile per hour reduction of mean speed depending on the absolute speed (Elvik et al., 2019).

On limited access roads, speed variation has also been shown to impact safety (Garber and Gadiraju, 1989; Taylor et al., 2000). This has resulted in a debate about how important speed variation is in safety. Further complicating this debate is the fact that speed variation has been found to decrease as average speed increases (Taylor et al., 2000). Some researchers entirely ignore the possible impacts of speed variation, with Davis (2002) calling the suggestion an "ecological fallacy" given the data from the studies demonstrating the effect are from aggregate cross-sectional data. In the literature, speed variation is also inconsistently measured across studies making it challenging to synthesize the relationship; in some cases, it is measured as the difference in traffic speed between peak and off-peak periods, in others the differences in speed between vehicles at a certain location, still others the difference in speed of a given driver. Because of the inconsistencies in definition of speed variation and the inconsistencies in the findings it is not clear if speed variation influences safety. Furthermore, we could find no research specifically concerning how speed variation impacts crash frequency or injury severity of collisions involving pedestrians and bicyclists in urban environments.

The effect of vehicle speed on the safety of bicyclists and pedestrians (vulnerable road users) is more challenging to measure due the lack of data on the exposure (volume) of bicyclists and pedestrians. In addition, because safety perceptions are a primary barrier to active travel (Fowler et al., 2017; Handy et al., 2002; Kerr et al., 2016), lowering vehicle speeds is likely to have implications on travel mode choice (i.e. more people choosing to walk and bike), which can lead to increases in safety. Although the causal mechanisms for this phenomenon are just starting to be studied, the correlation of low bicyclist crash rates with high bicycling volumes is known as "safety in numbers" (Elvik and Bjørnskau, 2017; Fyhri et al., 2016; Jacobsen, 2003; Jacobsen et al., 2015). We could find no studies following the full causal chain from change in vehicle speeds, to change in bicycling rates, to change in safety, so we cannot report any quantitative ranges of these effects.

Evidence for posted speed limit effects on safety outcomes

Statutory and posted speed limits are a mechanism that can be used to control car speed, but most studies suggest that effectively controlling speed relies on numerous other factors including enforcement of speed limits, features of the road (e.g. elevation gradient, road geometry, striping), land use, traffic control devices, etc. We attempted to extract only the estimated effects of speed limits in the following sections, but speed limits are not independent of these other factors so most observational studies are not enough to estimate the effect of speed limits. For that reason, we focus heavily on before-and-after studies.

Speed limits as determinants of vehicle speed

Reducing speed limits almost universally reduce speeds both on limited and mixed access roads (Elvik et al., 2004). However, the absolute magnitude of speed changes from speed limits alone are quite small. In Figure 1 we plot the data reported by Elvik (2019) and Silvang and Bang (2016) which include before-and-after studies of speed limit changes. The lines are nearly all upward sloping (increasing speed limits increases mean speed, and decreasing speed limits decreases mean speed), but the steepness of most of the slopes suggest that only a small fraction of the speed limit change is transferred to mean speed change. Figure 1 shows that 20-40% of the change in posted speed will be transferred to a change in mean speed. This indicates that a 5 mph reduction in speed limit is likely to decrease mean speed by 1-2 mph, and seems to be consistent across limited access and mixed mode roads (Figure 1). Reducing speed limits also reduces speed variance and reduces the speed of the fastest drivers to a much greater extent (Silvano and Bang, 2016), which may explain why the effects of reducing speed limits on safety are more notable (see below). With stronger enforcement, the effect of a 5 mph reduction in speed limit may be closer to 3 mph (60% of the speed limit change) reduction in mean speed (Islam et al., 2013).

In some road environments speed limits can play a more minor role on absolute vehicle speed. For example, curve radius is the dominant predictor of speed on horizontal curves (Othman et al., 2014), and lane width and vehicle redirection are the strongest predictors of speed in work zones (Paolo and Sar, 2012). Furthermore, enforcement is an important factor that is inherently linked to the effect of speed limits on driving speeds. It is very difficult to account for differences in police enforcement due to the varied nature of the practice across study sites, so some of the results from speed limit changes may be partially confounded by differences in police enforcement. Nonetheless, the current breadth of studies and reviews on this topic clearly indicate speed limits changes cause changes in drivers' speed.

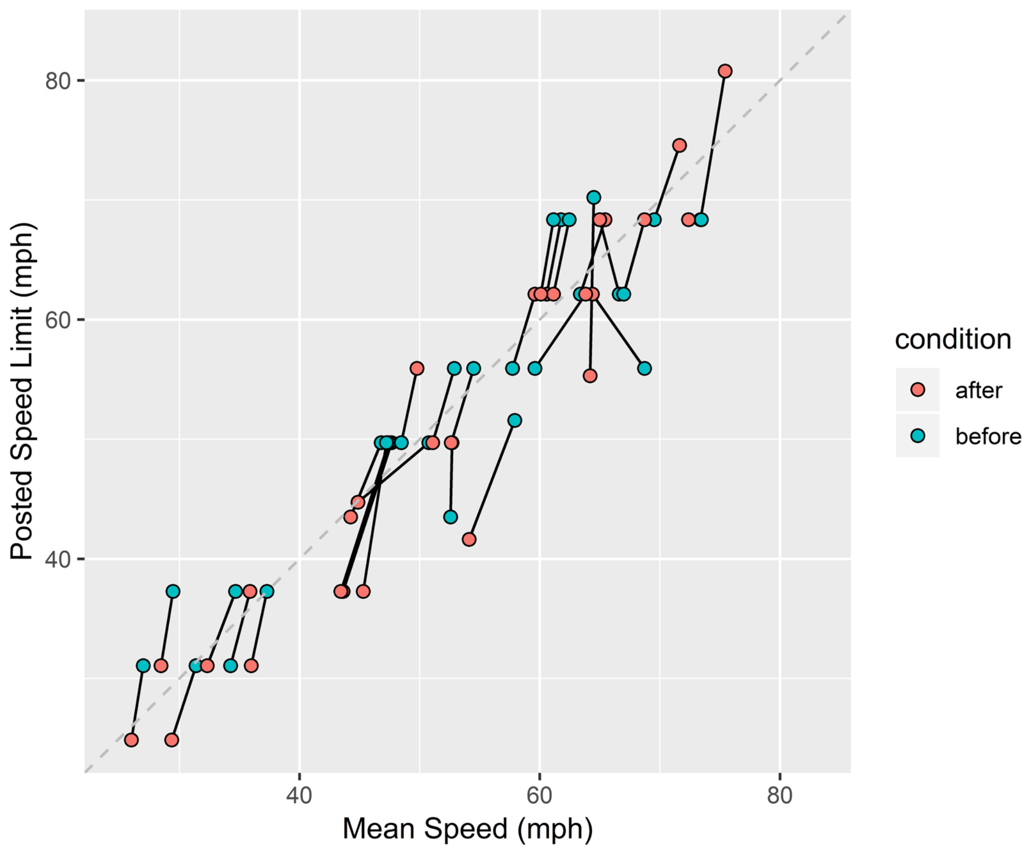

Figure 1. Elvik (2019) and Silvang and Bang (2016) posted and mean speeds from reviewed studies.

<u>Speed limits as determinants of crashes, injuries, and fatalities</u>

Using before-and-after studies in Sweden, Nilsson (1982) showed a 22-40% change in crashes to a 20 km/h (12.5 mph) change in speed limit (i.e. 2-3% reduction per mile per hour reduction). Since those experiments in Sweden, before-and-after studies of speed limit changes have been more widespread. In a recent review and meta-analysis, Elvik (2019) showed that most studies indicate even stronger effects. The studies reviewed by Elvik (2019) show the effect of a 5 mph reduction of speed limits on limited access roads to be roughly a 8-15% reduction in injuries but with outlier studies reporting reductions as great as 28% and 39%. A few studies find evidence for an opposing effect (negative relationship between speed limit reduction and frequency of injuries). The study in rural Montana indicated the potential for a small speed limit reduction (5 mph) to decrease injuries, but larger reductions (10-15mph) to increase injuries (Gayah et al., 2018). However, other studies with large speed limit decreases still find associated decreases in injuries (Elvik et al., 2019). Expected reduction in fatalities per 5 mph reduction in speed limit is nearly always greater than that of injuries in the same studies. The range of most studies reviewed by Elvik indicate 10-30% reduction in fatalities and one study as high as 80% (Hosking et al 2005) when reducing a speed limit by 5 mph. Two of seven Swedish cases in the review showed speed limit increases and associated decreases in fatalities (Elvik, 2019). Importantly, the most common effect in Sweden still showed increasing speed limits increased fatalities, although these results were highly uncertain due to the low fatality rate (Vadeby and Forsman, 2018).

In urban areas speeds are generally slower, but the density of vulnerable road users is generally greater. Many studies on the effect of low speed limit roads on bicyclist injury severity agree that low speed limit roads are safer. While the safety of low speed limit roads is likely due to many factors, a few studies indicate associations between posted speed on bicycling safety suggesting a 5 mph speed limit reduction would result in 2.2-15.2% fewer serious bicyclist injuries (Helak et al., 2017; Zahabi et al., 2011). However, these studies assume a linear effect of posted speed which is unlikely. More importantly, before-and-after measures of bike safety from speed limit changes are missing from the literature making valid effect estimates difficult. Other evidence for effects of speed limits on bicyclist safety come from broad cross-sectional examinations of crashes in different speed limit environments. While these studies don't isolate the effect of speed limits on safety, they provide broad evidence for the conclusion that lower posted speed roads (i.e. roads designed for slow speeds) are safer. In general, the magnitude of effects from these studies suggest that roads with speed limits of 30-35 mph have 17-32% more injuries and 21-45% more fatalities than roads with speed limits less than 30 mph, and roads with speed limits at or above 45 mph show 32-54% more serious injuries and 274-326% more fatalities than roads with speed limits less than 30 mph (Aldred et al., 2018; Chen and Shen, 2019; Helak et al., 2017; Kaplan et al., 2014; O'Hern and Oxley, 2018; Olszewski et al., 2019; Zahabi et al., 2011). Studies on the relationship between speed limits and pedestrian safety are like those for bicycling. Lower speed limit roads have lower odds of serious injury. For example, Hussain et. al. (2019) showed that environments with 5 mph lower posted speed limit equate to 56-88% fewer serious pedestrian injuries and 80-96% fewer pedestrian fatalities.

Conclusions

This research synthesis on the relationship between vehicle speed limits and road safety indicates that reducing vehicle speed limits will likely reduce vehicle speeds and improve safety across most road environments. The magnitude of the effects reported above are from a broad literature review on this subject but may not be representative of all global road environments. However, the current evidence clearly supports the use of reducing speed limits to increase safety in general. Even though reducing speed limits may only have a small effect on vehicle speeds, those changes in speed result in meaningful safety improvements. This may be especially the case for mixed-mode environments, where vulnerable road users benefit at much greater rates compared to drivers. While changing speed limits are a strategy for increasing road safety, they clearly are interconnected with many other strategies that should be considered, in which we cover in other sections of this research synthesis.

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3 History of Speed Management and the 85th percentile

3.1 A Historical Look at Crowdsourcing Speed Limits and the Question of Safety

By Brian Taylor and Yu Hong Hwang

ABSTRACT

The "85th percentile rule" is commonly used to set speed limits in jurisdictions across the U.S. Modern interpretations of the rule are that it satisfies key conditions needed for safe roadways: it sets speed limits deemed reasonable to the typical, prudent driver, reduces the problematic variance in travel speeds among vehicles, and allows law enforcement to focus on speeding outliers. Authoritative publications regularly assert that the rule came about because early driving surveys often found that drivers moving at or below the 85th percentile of a speeds on a given roadway were about one standard deviation above the mean speed for that roadway and were "in the low involvement group for traffic incidents" (Research Triangle Institute, 13). This conventional wisdom about the 85th percentile rule is increasingly called into question today by both safety advocates and promoters of more "complete" urban streets. Given this emerging debate, it's an opportune time to ask where this rule of driver-set speed limits came from and if the rule's developers' rationales still hold true today. While most observers trace the rule to safety research and a 1964 report, we find that it actually emerged decades earlier when "traffic service" was a preoccupation of the nascent traffic engineering profession during the first half of the 20th century, and likely a central motivation behind the development of the rule.

> As societies, we have gradually accepted faster and faster speeds as a necessary part of a life of increasing distances...Our cars have been engineered to bring a certain level of safety to these speeds, but even this is rather arbitrary, for what is safe about an activity that kills tens of thousands of people a year and seriously injures many more than that? (Vanderbilt 2008, 274).

SPEED RULES, SPEED KILLS

Motor vehicles give drivers, their passengers, and their goods remarkable freedom to move from almost any location to any other quickly, comfortably, and safely. Cars and trucks are so popular that much of the transportation engineering and planning professions are devoted to coping with and managing the movement and storage of the nation's 272 million vehicles (U.S. FHWA 2018).

One way of increasing the economic and social utility of travel is by getting people and goods to their destinations more quickly, but faster is not always better for everyone. Higher speeds increase the risks of crashes and system disruptions, and cause more injuries and deaths. Fast moving vehicles also increase emissions, noise, and disruptions of adjacent human activity. The challenge, then, is to balance the economic and social benefits of higher vehicle speeds on one hand, against the greater safety, environmental, and human activity costs of fast-moving traffic on the other. This is where speed limits come in.

Speed limits would not be needed if everyone drove at or below the speed that optimally balances these benefits and costs of travel, but not everyone does. So how should speed limits be set? This oft-debated question has long vexed traffic engineers. Drivers and commercial shippers frequently favor faster limits, while those living, walking, biking, or playing on or near roads often argue for slower limits. Walking, public transit, ride-hailing, cycling, and emerging forms of micro-mobility now compete with cars and trucks for urban streetspace, along with sidewalk cafes, parklets, and greenery, to create increasingly "complete" streets. With that influx of non-driver actors on streets and roads, concern over the safety of pedestrians, cyclists, and scooterers has grown. More and more cities aspire to the ideas of Vision Zero, which aims to eliminate *all* traffic deaths. To adjudicate these competing claims, traffic engineers have for decades depended on the 85th percentile rule to guide them in setting speed limits.

By examining the history and origins of the 85th percentile, this article seeks to shed light on current debates about speed limits. In the pages that follow, we trace the origins of the rule, review its evolving rationales, and close with a discussion of the logic of using drivers to collectively set speed limits in the context of our many, and often competing, goals for streets today.

RESEARCH APPROACH

This research builds on a recent UCLA Institute of Transportation Studies report on the 85th percentile rule (Toda 2018), and consists primarily of archival research of studies, articles, and older guide- and textbooks on traffic engineering and speed limit setting. Our primary focus is on the U.S. The University of California (UC) Library system, the UC Institute of Transportation Studies Library, and the digital Hathitrust Library were the primary resources used in sourcing the archival materials for this research.

SPEED LIMIT SETTING TODAY: A THUMBNAIL SKETCH

So what is safe speed? Who gets to decide? Engineers? Drivers? Pedestrians? Traffic experts, have tended to defer to drivers, rather than their own expertise, in no small part because the issue is so enormously complex.

The most common method for setting speed limits in North America is, according to the U.S. Federal Highway Administration's (FHWA's) 2012 guide to speed limit setting, the 85th percentile method (14). The "85th percentile" refers to the distribution of speeds traveled by vehicles on a given free-flowing stretch of roadway (**Figure 1**). To set an optimal speed limit, one conducts a survey of spot speeds (i.e. the speed of a car passing a certain point) to find the speed at or below which 85 percent of vehicles travel; the speed limit is then set at or near a five mile-per-hour value nearest that 85 percentile speed.

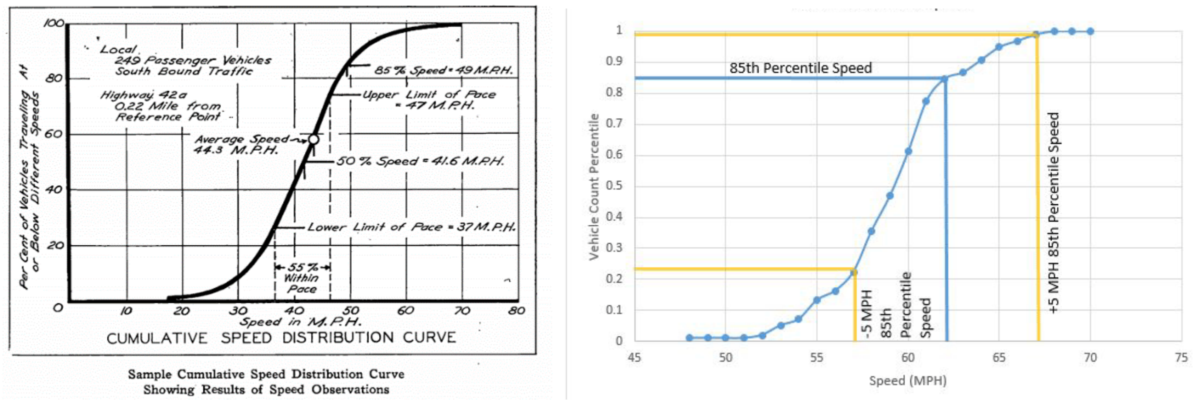


Figure 1: Examples of the 85th percentile speed in typical vehicle speed distributions in 1941 and 2019

Note: The diagram on the left is from a 1941 report by the Committee on Speed Regulation (Figure 9, 29); a version of this figure is in the 1950 *Traffic Engineering Handbook* and was reproduced in a 1958 traffic engineering textbook as well. On right is a screenshot from the ITE website taken in 2019 (Finkelstein).

That "85th percentile speed," according to the FHWA, "separates acceptable speed behavior from unsafe speed behavior" (Forbes et al. 2012, 12). Referring to "research at the time," the FHWA guide reports that drivers have an optimally low crash risk at or below approximately one standard deviation above the mean speed of free-flowing traffic, which in typical vehicle speed distributions is at about the 85th percentile speed in the distribution (Ibid). However, a footnote in this FHWA guide calls the assertions about safety into question:

> The original research between speed and safety which purported that the safest travel speed is the 85th percentile speed is dated research and may not be valid under scrutiny (Ibid).

The footnote goes on to suggest that interested readers should refer to a later section of the guide for more current thinking, which is that "for a given roadway type, there is a strong statistical relationship between speed and crash risk for speeds in the range of 15 mph to 75 mph" (Forbes et al. 2012, 4). Write Forbes et al.:

> The relationship between mean travel speed and crash risk can be adequately described in terms of [**Equation 1**]:

$$CMF = \left(\frac{V_a}{V_b}\right)^x \qquad (1)$$

Where:

CMF = Crash modification factor

V_a = Mean speed in the after condition

V_b = Mean speed in the before condition

X = 3.6 for fatal crash frequency

2.0 for injury crash frequency

1.0 for property-damage-only crash frequency

4.5 for fatalities

2.7 for personal injuries

> The relationship between speed and crash risk can be modified to some extent by road environment, vehicle-related factors, and driver behavior. But, the effects of speed on crash risk are remarkably consistent across different contexts (2012, 4).

While the FHWA guide describes the 85th percentile as grounded in safety, it also describes the driver-set speed limits set using the 85th percentile method as "attractive" because it reflects the "collective judgement of the vast majority of drivers" and aligns with the "general policy sentiment" that laws should not make illegal the actions of reasonable individuals (Forbes et al. 2012, 4, 12). As we will show, such deference to the collective judgement of drivers and concerns about creating too many lawbreakers – a logic unconnected to safety – can be traced back to the initial development of the rule.

In 1970, Joscelyn et al. examined the history of the 85th percentile rule and described a "newer theory" of speed and incidents, which was rooted in the idea that speed *variations* along a given roadway, more than absolute speeds, were the primary contributor to traffic collisions (94). Joscelyn et al. wrote that the "most noted" study on the matter had been conducted six years earlier by David Solomon (Solomon 1964), who was the Chief of the Safety Research Branch in the Traffic Systems Research Division of the Bureau of Public Roads, the predecessor agency of the FHWA. Solomon developed a U-shaped curve using data from prior studies showing a relation between deviation from mean speed and crash risk **(Figure 2)**.

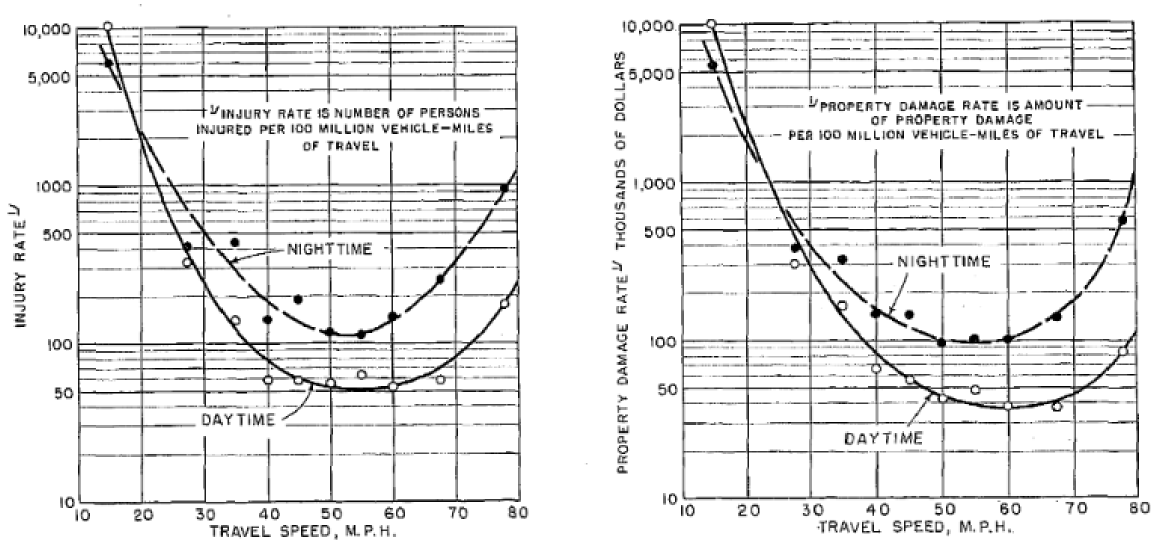


Figure 4.—Injury rate by travel speed, day and night.

Figure 5.—Property damage rate by travel speed, day and night.

Figure 2: The "U-shaped" traffic incident curves estimated by Solomon (1964, 13).

The vehicle speed-crash incidence relationship implied by Solomon's U-shaped curve was accepted in a subsequent study by a team at the Research Triangle Institute (RTI) led by Herbert Hill (and assisted by Joscelyn), though the curve was not as pronounced in the RTI study (Research Triangle Institute 1970, 13). These findings were then used by Joscelyn et al. in 1970 as evidence for their recommendation to the FHWA that the 85th percentile rule be used to set speed limits nationwide.

While Joscelyn et al. (1970) credited Solomon with developing the compelling evidence in support of the rule, they acknowledge earlier efforts to calculate percentiles of traffic speed distributions in order to set speed limits, including in a 1956 article by U.S. Chamber of Commerce Highway Transportation Specialist J.E. Johnston and in a 1955 Traffic Engineering textbook by Matson, Smith, and Hurd. Each of these sources made general assertions about the nature and merits of the 85th percentile rule, with Johnston writing that "many traffic engineers agree that a limit which includes 85 per cent of the drivers is reasonable" (Johnston 1956, 33).

Similarly, Matson, Smith, and Hurd (1955) wrote that the speed limit with the greatest effect on regulating spot speed would be "usually between the 80 and 90 percentile of the free-flowing speed" (60) and that "the lower 50 per cent of the speed range includes about 85 per cent of the vehicles" (62). But the history of the 85th percentile can be traced back yet further.

THE ORIGINS OF SPEED LIMIT SETTING IN THE U.S.

Roughly three centuries before Johnston, Matson, Smith, and Hurd were advocated using the 85th percentile rule to set speed limits, the legislature of New Amsterdam prohibited in 1652 "fast driving" by forbidding "Wagons, Carts or Sleighs" from being "driven at a gallop" within the city (O'Callaghan 1868, 128). Safety, vehicle speed, and traffic regulation were tied together as early as 1678, when the Colony of Rhode Island passed a law forbidding reckless driving of horses in response to a "very great hurte done to a small childe by reason of exceeding fast and hard riding" (Reeder et al. 1931, 4).

At the dawn of the last century, cities across the industrializing US were burgeoning and motor vehicles were being quickly added to an already chaotic mix of pedestrians, carts, horse-drawn wagons, and streetcars plying often disconnected, crowded, and lightly regulated city streets (Hill 1917; McClintock 1925). Pioneering urban transportation planner and engineer Harland Bartholomew referred to this as the "promiscuous" mixing of traffic that needed to be ordered and regulated (1926). With this early focus on ordering and regulation of streets to improve traffic flows, and soon thereafter on limiting the speed of galloping horses and the ever faster auto-mobiles filling city streets on safety grounds. It should thus come as no surprise that the first road sign would aim to bring order to that promiscuous mixing of traffic. Pioneering traffic regulation proponent William Phelps Eno claims that, in 1903, he proposed this first ever traffic sign to be used on U.S. streets (Figure 3) (1939).

Figure 3: The sign proposed by W.P. Eno (Eno, 1939).

The fundamental tension in speed regulation – between the benefits to drivers, passengers, and shippers of moving vehicles more quickly on one hand, and the elevated safety, pollution, and other costs borne by all users of street space due to faster speeds on the other – was apparent from the earliest days of traffic regulation. In 1925, Miller McClintock, then an Assistant Professor of Municipal Government at the University of California, Southern Branch (later known as UCLA) and consultant to the Los Angeles Traffic Commission, quoted a 1920 statement from Circuit Judge George Mix on the importance of improving traffic speeds:

> As a practical automobilist, when I went to the bench 1 ½ or 2 years ago, I recognized that [a speed limit of] 10 miles was unfair to the automobilist. I recognized that 10 miles per hour stripped the automobile of all its efficiency. You might better return to the horse-drawn vehicle days… or have automobile trucks driven for you at no greater rate of speed than 10 miles per hour (88-89).

However, in that same book, McClintock also cited traffic fatality statistics and concluded that, "The motor car has become the greatest destroyer of public life" (1925, 7).

A Nascent Science of Speed Regulation

In 1925, Physicist H.C. Dickinson and Assistant Mechanical Engineer C. F. Marvin, Jr. at the Bureau of Standards in the City of Washington wondered, "What is Safe Speed?" Remarking that "collisions cannot occur without something with which to collide," they argued for interconnected street networks on which safe speed would be determined by having a "clear course ahead" (Dickinson and Marvin 1925, 81). Calls of these sorts – to move activities unrelated to vehicular movement out of roadways, to better integrate the often disconnected urban street networks on traffic service grounds, and so on – were not new, and neither was touting their safety in addition to traffic service benefits. In making their arguments, Dickinson and Marvin presented a theory and formula for determining safe speed based on vehicle braking (deceleration), driver response lag times, and the degree to which there was a clear course ahead.

The idea of clear courses ahead spread in the late 1920s, and in 1930 the idea was referenced as the "clear space ahead" theory in *A Traffic Officer's Training Manual*, written by Clarence P. Taylor – who was at the time the Albert Russel Erskine Research Fellow at Harvard University. The theory, as articulated by Taylor, was hardly a conceptual breakthrough: "the farther ahead and to each side an operator can see, the faster he should be permitted to go, so long as he is able to stop his car in time to prevent a collision" (Taylor 1930, 104-105). In the manual Taylor also discussed the "two opposite views" of speed:

> One is that it is impossible to name any speed limit or limits that will be satisfactory under all conditions; and that there should be only a general rule making it unlawful to drive at any speed which may be dangerous. According to the other view such a rule is too vague, leaving too much to the judgment of the driver, and therefore a fixed limit is recommended (1930, 103).

Prima facie speed laws evolved out of the first of these views; under such laws, "definite speed limits are established, but beyond which a careful driver may go with impunity if conditions are favorable" since, according to Taylor, "speed alone is not hazardous" but is dangerous when "combined with dangerous practices" (1930, 104). While such laws (and attitudes) are present in many U.S. states today, Taylor offered no guidance on the determination of *prima facie* or maximum speed limits, clear courses ahead notwithstanding, saying only that *minimum* speed limits had considerable utility because "the laggard" motorist could disrupt traffic flows (1930, 108).

So by the 1930s, arguments for speed limits were mounting: both minimum limits on traffic service grounds, as well as maximums on safety grounds. But how should these limits be set? As the multitude of factors affecting optimal vehicle speeds became increasingly clear, and daunting, the search for a logical and consistent method of determining limits shifted from vehicles and the environments within which they moved, to the drivers piloting those vehicles.

LET THE DRIVERS DECIDE: THE RISE OF CROWDSOURCING SPEED LIMITS

In 1937, Wilbur Smith, a fellow of the Bureau for Street Traffic Research at Harvard University (and later a member of the Committee on Speed Regulation), argued in his 1937 dissertation, *A Scientific Establishment of Maximum Speeds,* for something conceptually akin to the 85th percentile rule. Smith wrote that the safest speed was near the top end of "the pace," the ten mile per hour segment of the speed distribution where most vehicles travelled (134). However, argued Smith, if more than 15 percent travelled above the top speed of pace, then a speed higher than the pace would likely be safe (Smith 1937, 134).

This deference to the majority would take root. Since most drivers did not crash their vehicles, the members of a National Safety Council (NSC, a nonprofit group that focuses on public safety) Committee on Speed and Accidents argued for the wisdom of allowing drivers to collectively determine safe driving speeds, saying "it is obvious that most drivers operate at safe speeds most of the time...considering that there is only one personal injury accident for every quarter of a million miles driven" (Committee on Speed and Accidents, 1937). Two years later, the logic of driver-set speed limits received another boost when the same NSC Committee, now known as the Committee on Speed Regulation, wrote that "the speed practices of the motorists on the highways are one of the best guides in the selection of speed limits" and noted that official NSC policy had been adopted to that effect (Committee on Speed Regulation 1939, 9).

THE 85 PERCENTILE AS *A STARTING POINT* IN SPEED LIMIT SETTING

Even while touting the logic of allowing reasonable and prudent drivers to determine appropriate driving speeds, experts at the time were clear that incidents should subsequently be analyzed and limits adjusted should evidence of too-high limits emerge. For example, in 1937 the Committee on Speed and Accidents produced an interim progress report on the imposition of speed limits that argued:

> A safe speed for any set of driving conditions is a speed at which a motorist can operate and have assurance of safety. Critical speeds are the limiting values for the range of speeds safe for the conditions. If the motorist exceeds the upper critical speed, he has no assurance of safety (2).

The NSC report included data on a speed survey in Buffalo, New York analyzing the 85th percentile speed roadways there (Committee on Speed and Accidents 1937, Table A-9). The report concluded by recommending that, *for a road with little to no collision history*, "it is reasonable to use the speed at or below which 80 or 90 per cent of the vehicles travel as a criterion of critical speed" (Committee on Speed and Accidents 1937, 4). So for the NSC Committee on Speed and Accidents, safety was something to be evaluated separately and subsequently to setting speed limits at the 80th, 85th, or 90th percentile of unregulated vehicle speeds.

A year later, in 1938, Harold F. Hammond and Franklin M. Kreml co-authored a pamphlet entitled, *Traffic Engineering and the Police.* Hammond was the Director of the Traffic division of the National Conservation Bureau (NCB, part of the Association of Casualty and Surety Executives, an insurance industry group) and Secretary-Treasurer of ITE; Kreml was the Director of the Northwestern University Traffic Safety Institute, Director of the Safety Division of the International Association of Chiefs of Police, and a member of the NSC Committee on Speed Regulation. In a section titled, "Holding Down Speed," the two wrote that:

> A practical way to arrive at a reasonable maximum speed is to assume that 85 per cent of the drivers are sufficiently careful not to operate their cars too fast for conditions. Thus that speed at or below 85 per cent of the drivers operate their cars may be accepted as the basis of computation. *It must, however, be adjusted in the light of accidents which have occurred and in which speed was an important factor*...A check back of accident experience is recommended for all methods employed by the traffic engineer. The importance of the check back in this kind of work is *not only recommended, but is absolutely necessary* (emphasis added) (Hammond and Kreml 1938, 42).

Again, the safety of speed limits set using 85th percentile speeds was to be evaluated separately and subsequently.

In 1941, the NSC Committee on Speed Regulation published a pamphlet advising that the 85 percentile speed was the safe speed for setting speed limits. The pamphlet, titled *Speed Regulation,* covered the essentials of speed and safety thinking, noted that:

> The numerical limit for a section being zoned should never be set at a value more than 7 miles per hour lower than the 85 per cent speed,* unless there are hidden hazards of an exceptional nature, *as revealed by the accident experience and by study at the location*.
>
> After establishment of a speed zone, if more than 15 per cent of the vehicles exceed a value of 5 m.p.h. above the numerical limit, the zone should be re-studied to determine whether the limit should be raised or whether there are other factors such as inadequate posting, or lack of enforcement or education (emphasis added, the asterisk (*) is from the original and notes that observations made at two or more locations should be averaged) (Committee on Speed Regulation 1941, 29).

Similarly, the ITE *Traffic Engineering Handbook*'s first edition was launched in 1941 and touted as a "pioneer work in a field in which the literature consists mainly of pamphlets, reports, and articles in professional journals…" (Hammond and Sorenson 1941, v). With respect to speed limits, the handbook offered that:

> Engineering formulae are recommended for calculating critical speeds at approaches to curves, hill crests and intersections with obstructions to view across corners. At other locations in need of zoning, prevailing speeds, *in combination with the relative accident experience*, are recommended for use in determining the maximum speed to be permitted there (emphasis added) (Hammond and Sorenson 1941, 200).

Recall that Joscelyn et al. (1970) noted mention of the 85th percentile in a 1955 textbook by Matson et al. That book, in turn, refers to the 1945 *Manual of Traffic Engineering Studies*, which claimed, "Generally it is considered that the 85-percentile is the safe speed, *if the accident record has been low*" [emphasis added] (NCB, 67).

Why would recommendations of ITE mirror those of the NSC? Ties between ITE and the NSC were close; some members of the Committee on Speed Regulation were prominent members of ITE. In fact, ITE was organized at the 19th Annual Safety Congress in Pittsburgh in 1930, a NSC event (Reeder 1931).

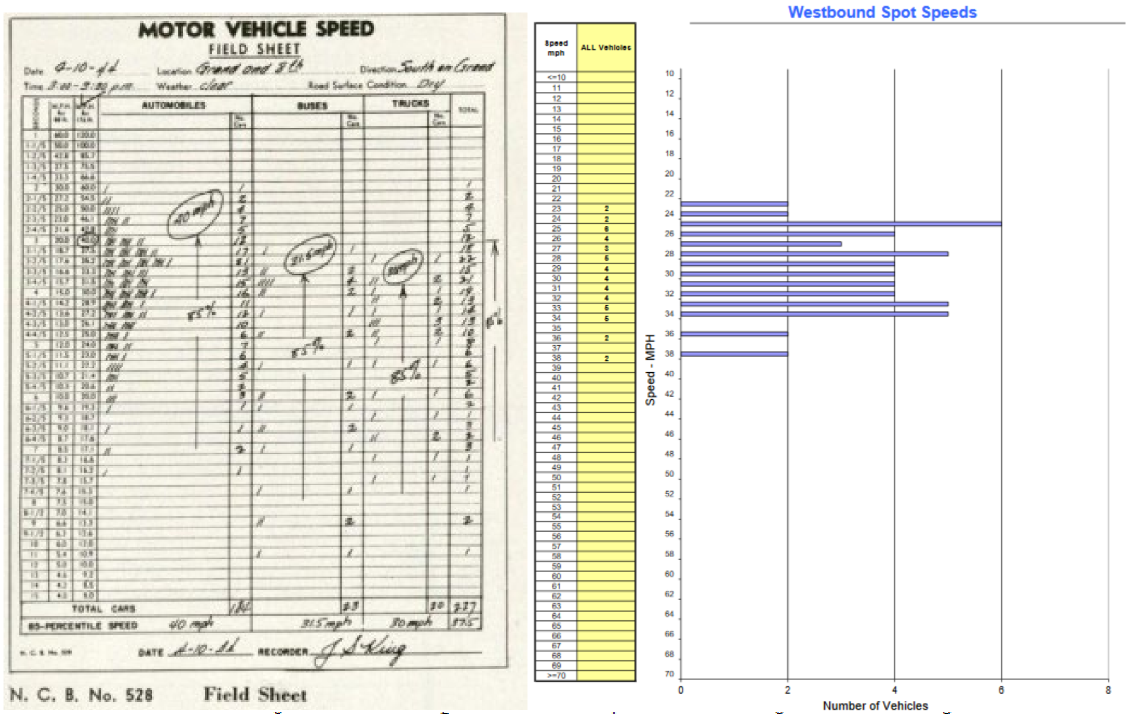
ITE would continue to recommend the 85th percentile rule into the late 1940s, and continue to call for subsequent speed limit adjustments based on analyses of speed-related incidents. According to a 1948 publication published jointly by ITE, the American Association of State Highway Officials (AASHO), and the American Public Works Association:

> The figure set on a section of highway should take into account the 85-percentile speed, since this shows what all but a few motorists consider reasonable. Too large a reduction in zoned speed below the 85-percentile speed may therefore involve enforcement difficulties. Nevertheless, where there are hidden or unrealized hazards of an exceptional nature *as revealed by an accident experience study of the location it may be wise to post a zoned speed considerably lower than the 85-percentile speed* (emphasis added) (Joint Committee 1948, 34).

At the risk of belaboring the point, these several examples show that the originators of the 85th percentile rule in the 1930s and 1940s saw considerable wisdom in setting speed limits based on the behavior of typical, prudent drivers, but were clear that such drivers would not always travel at the optimally safe speeds for a given road segment, and that adjustment on safety grounds might be necessary.

THE 85TH PERCENTILE SPEED BECOMES THE *SAFE* SPEED

As early as 1941, the NCB was drawing on the work of ITE and others to market forms and instructional pamphlets on traffic engineering. Figure 4 shows a speed survey form based on the 85th percentile from the 1945 edition of the *Traffic Survey Manual* (which could be ordered for 1 cent, with reduced rates for large quantities (NCB, 115)).



Number of Vehicles

SPEED PARAMETERS										
Class	Count	Average Speed	Range	50th Percentile	85th Percentile	10 MPH Pace	# in Pace	Percent in Pace	% / # Below Pace	% / # Above Pace
ALL	52	29.6	23 - 38	29 mph	34 mph	25 - 34	44	85%	7% / 4	8% / 4

Figure 4: Example field speed analysis sheets from 1945 and today

Note: The "speed parameters" at the bottom of this figure is part of the modern sheet. The 1945 separates automobiles, buses, and trucks, while the modern sheet simply notes "Class: ALL." The sheet from 1945 also notes pavement condition and weather on the sheet. Measurement of the 85th percentile speed also required a measured distance of 88 or 176 feet and converting the number of seconds through that distance to speed in MPH, rather than simply measuring MPH as is possible with modern tools (NCB and ITE 1945, 67; City of West Hollywood, 2016).

Over time there were increasing references in the literature to using the 85th percentile rule to establish *safe* speed limits, but the calls for follow-up safety evaluations and possible adjustments began to be omitted. With the consistent focus on improving traffic service for ever-expanding motor vehicle fleets, the focus on regulating speed for safety receded, though it did not disappear. Thus, discussions of the 85th percentile rule began to conflate traffic service, speed variance reduction, and safety goals.

For example, in discussing *Speed Regulation and Control on Rural Highways* in 1940, Raymond G. Paustian, a research engineer for the Highway Research Board (HRB, the precursor of the Transportation Research Board) and an assistant professor in civil engineering at the Iowa State College of Agriculture and Mechanic Arts, asserted without empirical evidence that:

> ...there is some agreement among traffic engineers that the safe speed at a given location should be about the same as that at or below which 85 percent of local operators drive (17).

Similarly, Norman Kennedy, Professor of Transportation Engineering at the Institute of Transportation and Traffic Engineering at UC Berkeley, said this about the 85th percentile and safety in 1958:

> The drivers exceeding the 85th percentile are usually considered to be driving faster than is safe under existing conditions. They represent the primary problem of safety. The 85th percentile is a good guide in determining the proper speed limit (Kennedy et al. 1958, IV-5).

Leading up to the estimation of the Solomon Curves in the mid-1960s, perceptions of the 85 percentile rule had evolved. What began as a starting point to be subsequently evaluated in terms of safety evolved into a best practice "agreed upon as safe" (Paustian 1940, 17) and "reasonable" (Johnston 1956).

A 1963 literature review by Lester R. Jester, at Purdue University, addresses the ascendance of the "85th percentile is safe" perspective explicitly in a hypothetical 1957 argument between proponents of competing schools of thought. First:

> There is a recognition that the 85-percentile speed may be the most practical basis for setting many speed limits, although if accident experience shows that fast driving is a major contributing factor, there may be some merit in restricting operating speed below the apparent 85-percentile demand point (75).

Second, and the position supported by Jester:

> Properly established speed zones assist the motorist in selecting speeds that are safe, and permit him to obtain the maximum utility, economy, and convenience from his vehicle and the road. In general, drivers tend to observe speed limits that are reasonable, proper, and safe for existing travel conditions and disregard speed limits that are unreasonably high or low. The best way to determine a reasonable, proper, and safe speed limit for a particular location appears to be by measuring the speed below which a high percentage (85-90%) of the motorists travel (Jester 1963, 86).

If you outlaw driving fast, all fast drivers become outlaws

Lurking in much of the early research on vehicle speed regulations is the notion that drivers ignore limits on their driving speeds, particularly when those limits are below their driving comfort levels. Such low speed limits could be on well-founded safety grounds, or speed traps, or the result of complaints from those living near the roadway.

In 1941 the Committee on Speed Regulation recommended using the 85th percentile to keep from setting limits too low, arguing that the "limits *must* be reasonable to gain the respect of the motorist." Eight years later, University of Illinois Professor of Highway Engineering C.C. Wiley and his team found that "Traffic consistently ignores posted speed limits...and runs at speeds which the drivers consider reasonable, convenient, and safe under existing conditions," and that "The general public gives little attention to what speed limits are posted" (1949, 6).

Wiley, in the ITE proceedings the following year, sarcastically dismissed the principles of what would emerge a half-century later as the Vision Zero movement by criticizing a proposed "60 [mph] day-50 [mph] night" speed limit (1950, 51):

> The puzzle is, where did those numbers come from? As good a guess as any is that the 50 was obtained by dividing 100 by 2. As for the 60 maybe..a report...correlating fatalities with speed brackets. It showed that about 12% of fatalities occur at speeds over 60 mph. Therefore! Eliminate speeds above 60 and reduce fatalities 12%. A fine example of the misuse of the "rational" method, so let's follow it a little further. The same report said that about 12% of the fatalities occurred at speeds under 20 mph. So, eliminate those low speeds and save another 12%. That would leave 76% between 20 and 60 mph. Eliminate those speeds and get rid of all accidents. The only safe speed limit thus comes out as **zero.** The real value of that report, however, is that it shows that accidents occur in all speed ranges and that low speeds are just as guilty as high speeds (Wiley 1950, 51).

Concluded Wiley, "Who should establish the speed limits? Choose whom you may, but the final job will be done by the traffic itself…" (Wiley 1950, 51). Such arguments contain elements of reason – that most drivers are prudent, and prudent drivers know best – but might also be construed as pragmatic capitulation to mob rule.

J.E. Johnston in those same ITE proceedings laid out in less histrionic terms the mid-century state of thinking on speed regulation:

- The driving public has lost its respect for most traffic control devices including speed signs due to their promiscuous and indiscriminate use.
- The majority of drivers are good drivers. A reasonable speed limit will include the majority of good drivers.
- Speed limits designed to regulate the reckless drivers unduly penalize the majority and do little to change his reckless character.
- Speed regulations should be designed to fit the good drivers or the suit made to fit the man rather than the man to fit the suit.
- We have been posting minimum rather than maximum limits. Speed limits should seem too fast to the majority or it is not a maximum limit.
- There are three objectives in speed control:
    - Tend to slow the fast drivers
    - Tend to speed up the slow drivers
    - Tend to increase the percentage within the pace
- The application [of the 85th percentile] does the most to accomplish those objectives.
- The speed problem is one primarily of speed differential.

DIFFERENCES OVER SPEED DIFFERENCES

Long before Solomon, Taylor summed up the essence of the slow-vehicle problem that would be studied in more detail some three decades later:

> Thus far minimum-speed limits are not in general use, but their utility is widely admitted. The laggard congests and delays traffic, and on narrow, heavily traveled ways creates dangers through the necessity of overtaking. Often one or two slow drivers collect a long line of impatient motorists; and if the last car cuts out of line to pass the rest, it may be impossible to reach the head of the line before meeting an approaching car (1930, 107-108).

Much of the modern rationale for the 85th percentile, regarding the standard deviation of speeds and the risk curve, is based on Solomon and others in the 1960s, as discussed at the outset. Far from revelatory, this work supported the “conventional wisdom” at the time on the safety of 85th percentile speeds and was thus widely accepted with little scrutiny.

More recent studies of the vehicle speeds, crash risk, and the U-shaped curve have been less forgiving. Said Fildes and Lee in a 1993 review:

> [In] most of these studies [from the 1960s], it is impossible to assess the effect of inaccuracies or gross errors on the findings... Furthermore, most of the studies focused on particular settings (e.g. rural highways) and assumed that these findings apply equally to all roads and all environments (1993, 9).

In a 2009 analysis of studies from the Solomon Curve era, Hauer found that removing turning movements from the analysis significantly flattens the U-shaped curve (2009), suggesting that speed variance may be less of a risk than previously assumed. And in the 2012 FHWA speed regulation guide, Forbes et al. noted that:

> [Equation (1), which reflects more recent data on vehicle speeds and crashes] is significantly different from the traditional U-shaped relationship that has defined much of the current North American thinking on speed limits and speed management. The U-shaped relationship (Solomon curve) between speed and crash risk can be questioned for two reasons:
>
> 1. The U-shape is generally expected to be an artifact of errors in the measurement of speed; and
>
> 2. There is a strong correlation between mean speed and speed variance, so it is difficult to separate the effects of mean speed and speed variance on crash risk (4-5).

Such criticisms of the call into question assumptions about the safety of setting speed limits using the 85th percentile rule – an assumption we have shown that the originators of the rule never asserted. Thus, it would appear that the 85th percentile rule is back to where it stood eight decades ago: a reasonable starting point for speed limit setting, subject to adjustments if warranted by speed-related safety conditions.

CONCLUDING DISCUSSION AND IMPLICATIONS FOR TODAY

> The alarming increase in street accidents and in street congestion during the past few years has rendered the correction of traffic conditions one of the most important municipal problems of the present day.

While this quotation could easily be of a locally elected official in 2019, it was in fact penned by Miller McClintock in 1925 (vii) as a call to bring order to urban streets. A quarter of a century later, J.E. Johnston concluded that there were three goals of vehicle speed regulation: (1) to slow fast drivers, (2) to speed up slow drivers, and (3) to reduce variance in vehicle speeds. But while the solution then was to separate road users by type, and to move those not in vehicles onto sidewalks or into buildings, the solution increasingly proffered today is to move many of those activities back into streets to make them more complete, less dominated by driving, and, ideally, safer.

As a result, while Johnson’s three objectives for speed regulation may still have merit today, there are surely others:

- Create safe, attractive environments for walking
- Encourage bicycling and other “green” forms of mico-mobilty
- Prioritize public transit vehicle movements over private vehicle movements
- Accommodate personal and commercial shared-ride pick-ups and drop-offs

- Encourage economic and social activities (such as vending, shopping, and eating)

Viewing urban and suburban streets as complex economic and social spaces in which the movement of people and goods is but one of many primary purposes, calls into question the wisdom of having motor vehicle drivers determine appropriate travel speeds – particularly if a public policy aim is to reduce their share of urban street users over time. Indeed, the National Transportation Safety Board (NTSB) reports that, "The overwhelming safety factor for a vehicle striking a pedestrian remains the physics of differential mass (the weight and size of a pedestrian compared with that of a vehicle), plus the lack of protection afforded pedestrians. Consequently, of primary importance is mitigating speed or avoiding impact" (NTSB 2018, 16).

The wisdom of having drivers crowdsource speed limits via the 85th percentile rule might erode further if the injury and death risks to drivers and their passengers increasingly diverge from those of other street users (such as cyclists and pedestrians). While drivers are unlikely to ever become indifferent to crash risks, ever safer vehicles (equipped with crumple zones, airbags, anti-lock brakes, automated braking systems, etc.) may reduce risks to the occupants of vehicles more than to those on streets outside of vehicles, causing the risks of speed to those in and outside of vehicles to diverge further.

About four in ten respondents to a recent survey conducted by the American Automobile Association (AAA) admitted to driving ten miles per hour or move above the speed limit on residential streets, even as 90 percent of them reported being somewhat or completely disapproving of that behavior; and 64 percent reported thinking that doing so was very or extremely dangerous (AAA Foundation for Traffic Safety 2019). Similar data abound; McMillian and Cooper reported on a 2017 National Traffic Safety Board finding, writing that "that national, state, and local traffic safety stakeholders felt that unlike other crash factors such as alcohol impairment or unbelted occupants, speeding has few negative social consequences associated with it and that the public largely underappreciates the risks associated with speeding" (2019, 2). And a 2008 survey of drivers in Indiana found that, "A key motivating factor in drivers' tendency to exceed the speed limit is that they believe that the excess speed does not threaten safety" (Mannering 2009, 1).

So what to make of our practice of crowdsourcing speed limits via the 85th percentile rule? This paper has shown that the rule was developed in the first half of the 20th century, not to be the final word on speed limits, but as a starting point that balanced numerous competing objectives and interests. But after eight decades, vehicles are different, our aspirations for the uses of streets are different, and our safety goals are more ambitious – but the "rule" remains the same. The 85th percentile remains valid today:

1. If, absent posted speed limits, 15 percent of drivers will drive faster than is safe to do so over a given stretch of road, while 85 percent of drivers will drive at or below safe speeds.
2. If condition #1 does not vary significantly:
    a. Across states and regions;
    b. Among cities, suburbs, and rural areas;
    c. By the mix of drivers in the traffic stream (with respect to age, gender, familiarity with the road, trip purpose, and so on);
3. If conditions #1 and #2 have not changed significantly over time or in light of efforts to create more "complete" streets that host social and economic activity on sidewalks and in parklets, more bikes and scooters in the roadway, and more pedestrians crossing trafficways.
4. And if what an 85th percentile driver *feels* is an optimal travel speed (balancing personal utility and risk) is *actually* optimally safe for occupants (both those in and outside of vehicles) of a given roadway segment.

That's a lot of ifs. Or, as Vanderbilt puts it: "Leaving it up to drivers to figure out safe speed is risky business" (2008, 182).

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: (1) study conception and design – Brian D. Taylor; (2) data collection – Yu Hong Hwang; (3) analysis and interpretation of results – Brian D. Taylor and Yu Hong Hwang; (4) draft manuscript preparation – Yu Hong Hwang and Brian D. Taylor. All authors reviewed the results and approved the final version of the manuscript.

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4 Limitations of the Current Speed Limit Setting Practices

4.1 Limitations of the 85th percentile for highways and local streets

By Offer Grembek

Overview

Transportation safety professionals strive to build a system on which no street user can be severally, or fatality, injured on. To accomplish such a safe system, it is necessary to effectively harness all the core protective opportunities provided by the system. For example, if we're looking at bicycle safety we would want alert and compliant cyclists and other road users, to make trips using safe bicycles and safe vehicles, on safe street design with adequate separation from motorized traffic, all of which are governed by safe speeds, and supported by effective cyclist protection and the medical emergency system when needed. While many of these protective components are discussed in the academic and professional literature, the topic of safe speeds has always the subject of much debate outside of professional circles too. At the heart of the debate is the intuitive trade-off between speed and safety (Hauer 2009).

On the one hand, we have physical and biomechanical principles that establish the fact that when we travel faster, we carry higher levels of kinetic energy which would need to be safely dissipated when something goes wrong. So, given the exact same circumstances going faster reduces safety. On the other hand, there is the claim that ultimate safety can only be obtained with zero mobility (aka no movement) so we should establish some criteria to determine what can be considered safe speed. This discussion transcends the academic realms since setting speed limits is a decision that is critical for operational, legislative, enforcement, and political matters.

In the US, the professional community has addressed this by adopting the practice of setting speed limits to the 85th percentile of the speed distribution. While this document does is not assembled for resolving the debate about speed and safety, it will provide a summary of the literature as it relates to the limitations of the existing practice.

Limitations for Highways: speed creep

Safe speed cannot be determined in isolation of vehicle design, road design, and the anticipated road users. Each of these components play a role in contributing to the safe dissipation of the kinetic energy that is carried, and the overall impact can be considered additive (Mooren et al 2011). Similarly, the choice of traveling at a certain speed is also a product of vehicle design, road design, and behavioral considerations (). In light of this, there seems to be a preliminary alignment between the components that drivers use to select travel speed and those which are used to assess safety by the professional community. While the initial logic of the 85th percentile methods seems reasonable, it begins to fall apart as we take a closer look at the conjectures at hand.

We will first examine the driver's response to changes in the speed limit based on speed distributions on rural interstates in Montana between 1979 and 2007 as shown in Figure 1 and discussed in Hauer 2009:

"*The horizontal axis is in quarterly units, except for years 1982 to 1986 and for the "gap" years (1986 to 1995) where no speed data were collected, and the increments are annual. The solid line is for the 85th percentile and the dashed line for the median speed. Between 1979 and April 1987, the speed limit was 55 mph. From there until December 1995, the speed limit was raised to 65 mph. Whether there was a jump in April to May 1987 cannot be said because data collection stopped until 1995. A backward extrapolation of the later trend indicates that a jump in speed likely occurred. In December 1995 Montana adopted the "Basic Rule," which prevailed until the end of May 1999. According to the Basic Rule, daytime speeds should not exceed what is "reasonable and prudent" in a police officer's judgment, while the nighttime speed limit remained at 65 mph. On May 28, 1999, Montana abandoned the Basic Rule and raised the speed limit to 70 mph.*"

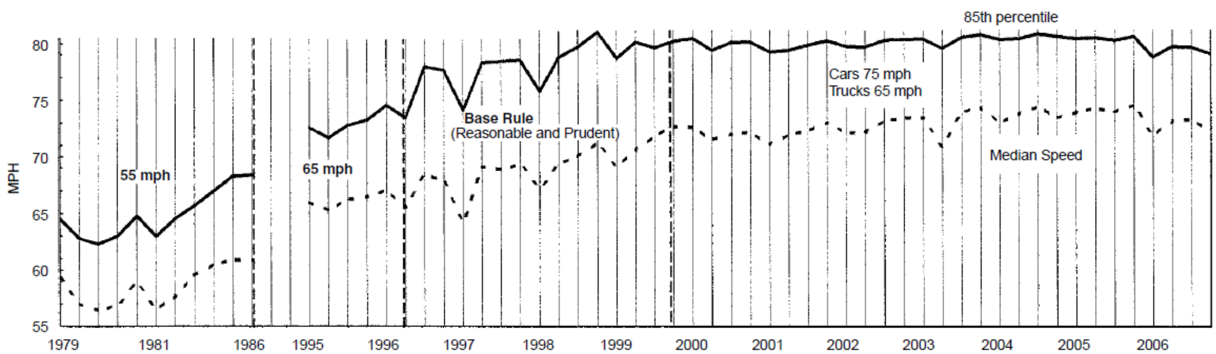

FIGURE 1 Median and 85th percentile speeds on rural Interstates in Montana. (Source: R. Retting of the Insurance Institute for Highway Safety and Hauer 2009).

When reviewing the change in the 85th percentile and median speed as it relates to the speed limits once can observe a steady upward creep in speed that, over the nearly two decades, amounted to 10 to 15 mph and continued even during times when the speed law and the road remained the same. According to Hauer 2009, the practice of the 85th percentile can explain such speed creep:

"One such mechanism could be the practice of setting the speed limit by the 85th percentile of the speed distribution. For example, assume that collectively drivers elect speeds such that about half of them drive faster than the speed limit. This behavior, if coupled with a periodical application of the 85th percentile rule, would cause an upward drift in speeds as illustrated in Figure 2."

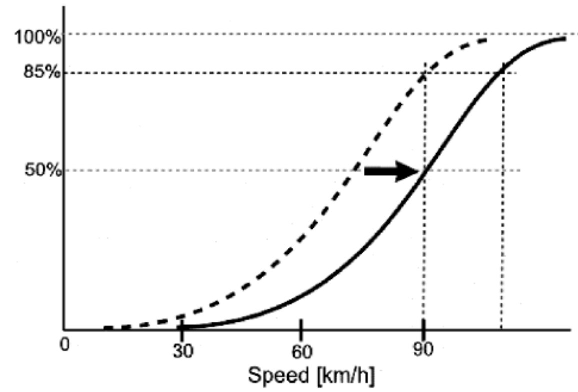

FIGURE 2 Speed distributions before and after change in speed limit. (Source: Hauer 2009).

While there can be other ways to explain this speed creep, the 85th percentile is a very plausible mechanism that can result in such an outcome. Moreover, between 2000 and 2007 the vehicle fleet continued to introduce additional safety features as in past decades, but there is no visible response to the this increase. This also undermines the conjecture that drivers are able to incorporate roadway and vehicle design consideration into their selection of safe travel speed. The insights from this, are that while road design and vehicle design are elements that drivers use to select travel speed, the actual speed limit is likely to carry the highest weight in determining one's travel speed. Other research also shows that drivers are much less likely to adapt to things that they cannot perceive, it is unlikely that they are able to perceive the some safety features provided by cars (Grembek, 2010).

In light of this, it is much more likely that the speed creep is a response to raising speed limits and that this practice results in higher travel speed even if the road and vehicle conditions remain the same.

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Limitations for Local Streets

Behavioral limitations

Drivers have a tendency to underestimate speed (Recarte et al., 1996). This can range from an underestimate of 10% at higher speeds (70 mph) and up to 30% at lower speeds (35 mph). This demonstrates that drivers have limited capability to self-regulate a safe speed at lower speed areas.

Another important behavioral limitation is that a key motivating factor in drivers' tendency to exceed the speed limit is that they believe that the excess speed does not threaten safety (Mannering, 2009).

Another important distinction between highway and local roads is the perceptual role of a guardrail and in defining the perceived safety margins that various shoulder widths provide (Ben-Bassat, 2011). Local streets often lack of strong visual cues for drivers to assess safety and speed.

These items show that the conjecture that safe speed limits should be determined based on the actual driving habits of drivers cannot be used to establish safe travel speeds on local streets.

Weather conditions

This becomes even more problematic when the weather is not ideal. A study in a virtual simulated environment showed that the sense of speed decreases in fog and as a result drivers think they are driving far more slowly than they actually are in foggy conditions (Snowden et al, 1998). This demonstrates that under some conditions drivers' under-estimate their speed and accordingly overestimate the safety of their trip.

Deterrence Theory

As discussed earlier, a driver's choice of travel speed is to some extent based on the inherent desire to avoid damaging events to people or property. However, this motivation is occasionally an insufficient deterrent and has to be complemented with legal sanctions (Jacob 1980). Deterrence Theory dictates that compliance with laws is associated with the certainty, severity, and swiftness of punishment, where certainty represents the likelihood that a violator will be punished, severity represents the extent of the punishment, and swiftness represents the time between the violation and the punishment (Tay 2005, Stafford 1997). Perceptions of certainty, severity, and swiftness of punishment for particular violations are derived from personal experience (specific deterrence) or from vicarious experience (general deterrence), with some research showing that the certainty of punishment has a largest effect (Tay 2005, Jacob 1980). Drivers commonly establish a perception of the associated legal sanctions for many traffic violations such as speeding. These perceptions are based both on punishment and punishment avoidance experience, since it is possible to commit violations without suffering any consequences. In light of this, the impact of the legal deterrence to speeding is strongly driven by the perception of enforcement. Speed enforcement on local streets is typically limited and lower than on highways. Accordingly, the perception of certainty is reduced and the overall impact of legal sanctions as a deterrence for speeding on local streets is diminished.

Theory of planned behavior

Theory of planned behavior (Ajzen 1991) and bounded rationality can provide a good framework to show how reasonable human behavior can result in driver's underestimation of high chances of avoiding a crash, and how at moderate speeds the severity of a potential collision was overestimated. (Schmidt-Daffy)

Spatial speed creep

Studies have shown that higher speeds on some highways causes higher speeds on connecting local roads (Casey et al, 1992). The implication of this study is that the impact of speed limits on highways can be carried over to local streets and should be considered.

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5 Alternatives Approaches to Setting Speed Limits

5.1 Setting speed limits in other countries and recent domestic developments

By Katherine Chen and Offer Grembek

Approaches from other countries

Excess speed and inappropriate speed for the prevailing conditions occur with regularity globally. Transportation professionals must understand how vehicular speeds relate to fatal and serious injuries, the factors essential to designing roads for safe speeds, mobility, and context, as well as speed management policies that consider elements crucial to providing a safe environment for all road users.

The human body is vulnerable and unlikely to survive impact speeds of more than 30 km/h. Based on this understanding, international best practices aim to minimize the severity of road traffic crashes through such programs as Vision Zero, Sustainable Safety, and Safe Systems. Though termed differently per country, many of these programs share common principles and strategies. The following are a few case studies of speed management internationally.

<u>Netherlands</u>

Speed limits are about finding the optimum balance between safety, mobility, and environmental considerations. The Netherlands adopted “Sustainable Safety” as a vision in 1992; this paradigm shift uses safety as a design principle for the road traffic system and emphasizes how to prevent human errors to the extent possible and how to minimize the severity of a crash. The Dutch adapted their road system to the limitations of human capacity, of human tolerance. They consistently apply three key principles - functionality, homogeneity, and predictability - across their three road types - through-roads, distributor roads, and access roads - to achieve their sustainable safe traffic system (Wegman, Dijkstra, Schermers & Vliet, 2005, p. 9).

The Netherlands expanded 30km/h zones from 15.5 percent of their urban residential streets to 54.5 percent (exceeding their goal of 37.2 percent) by adopting a “low-cost” approach that allows for phased introduction and realisation of the new speed limits (Wegman, Dijkstra, Schermers & Vliet, 2005, p,20). In the short-term, communities posted the new speed limit with some support of traffic calming devices with the goal to transform the area through engineering so the new speed is clearly evident to drivers.

They also introduced the 60km/h zones, down from 80 km/h, through the same Start-up Programme for rural access roads that met a specific criteria warranting reduced speeds to improve safety for vulnerable users and/or located in transition zones (Wegman, Dijkstra, Schermers & Vliet, 2005, p,22). Within these zones, they also introduced a new design element with broken line markings on both sides of the motor vehicle lane clearly reserving space for cyclists on the roadway. This lane division did not physically separate the roadway but allocates “space” for each type of user. Evaluations found lower average driving speeds on these roads and cyclists stay in ‘their’ lane on these rural access roads.

Other elements of the Start-up Programme on Sustainable Safety included changes in policy where all traffic (excluding pedestrians) approaching from the right has priority right-of-way, installing roundabouts, and changes to moped operating behavior (helmet requirement, reduced speeds, limiting road access). Ultimately this program was successful because it had buy-in from all tiers of government with an agreement that contained specific action plans aimed at changing the road infrastructure and a 110 million Euro subsidy from the central government.

The Netherlands and the European Union recommend posting 'credible speed limits' which is a limit that the majority of drivers consider a logical speed for that specific type of road in that specific road environment (SWOV, 2012). Because credibility functions on a sliding scale and is not an absolute measure, transportation professionals must select a limit that is *more* credible for everyone to promote compliance resulting in average driving speeds closer to the limit with smaller speed differentials between operators.

The starting point for credible speed limits must be a *safe limit*. If a speed limit is incredible, transportation professionals have two options to either change the limit or to change the layout of the road or environment. Factors for setting a credible speed limit include the built environment including roadway features and geometry as well as dynamic elements like congestion and weather. Studies found that open surroundings and road width have the largest impact on speed and that features like a bend in the road and clarity of the road ahead influence all driver behavior (SWOV, 2012, p.2). Increasing limits to achieve a credible speed limit is typically less preferable to altering the road image. Credibility of speed can also be improved with dynamic speed limits that account for the current circumstances. This is particularly common in other parts of the European Union, including France, Finland, and Sweden (Wegman, Dijkstra, Schermers & Vliet, 2005, p,16).

Sweden[1]

Sweden adopted the "Vision Zero" road safety philosophy in 1997 with the long term goal that no person should be killed or seriously injured in road traffic. Their system relies on two principles: 1) human life and health are the top priority when designing roads; and 2) road traffic safety is a shared responsibility between all road users and system designers.

Sweden designed their road system based on what the human body can endure in both a vehicle-vehicle and vehicle-unprotected user (e.g., pedestrian, bicyclist) collision scenario. As part of the safe system approach, Sweden introduced median barriers to prevent head-on crashes, safer roadsides, traffic calming, roundabouts, separation, and reduced speed limits/differentials.

Sweden acknowledged the differences between urban and rural roads, resulting in the implementation of parallel efforts in these areas. They reviewed their national rural road network and established guidelines for each road type classification balancing traffic safety, environment, and mobility and accounting for regional differences. This resulted in a statistically significant reduction in the mean speed of passenger cars. For speeds in urban areas, Sweden established guidelines that consider the city's character, accessibility, security, traffic safety, and health and environment. This resulted in a mean speed decrease of 2-3 km/h. Under the safe system approach in Sweden, speed limits were reduced to prioritize the highest levels of safety.

[1] Vadeby, A. (2015). *Vision Zero and New Speed Limits in Sweden.*

Australia [2] [3]

The New South Wales (NSW) Roads and Traffic Authority (RTA) adopted the Safe Systems approach as a model to develop and implement road safety programs, with safer speeds and speed limits as essential components. Of particular emphasis is the need to educate the public about the dangers associated with lower-level speeding. The Safe Systems approach was adopted in 2004 and is guided by the vision that no person should be killed or seriously injured on Australia's roads and that the road system should be "better adapted to the physical tolerance of its users". It has a target to reduce the annual number of road crash fatalities and serious injuries by 30 percent by 2020.

The Safe System approach includes safer people, roads, vehicles, and speeds collectively and reinforces that the determination of safe speed limits must account for a myriad of factors, including hazards, the road environment, and the movement and presence of different road users. It suggests that those who design, operate, and manage the road system are responsible for the safety of the network.

NSW identified collision data issues related to collection, classification, and processing as part of their Safe Systems approach and are working to refine their policies to improve crash data. In contextualizing their understanding of speed as a contributor to collisions, excessive or inappropriate speed is considered by the Centre for Road Safety as the primary behavioral factor in traffic fatalities in NSW, especially compared to other jurisdictions.

The report emphasizes the need for cultural and behavioral change around the acceptability of speeding; while tolerance for high-level speeding is decreasing, the acceptance for low levels of speeding is increasing. It highlights that a small increase in speed results in a large increase in braking distance. Cumulatively, minor speeding is a greater danger to the community than excessive speeding given the higher volume of drivers engaged in risky behavior. The report concludes that there needs to be increased awareness, e.g., public education campaign, about the impact of low-level speeding on crash outcomes.

NSW found that point-to-point cameras are effective at improving compliance with the posted speed limits and recommends extending its use to all vehicle types. Transport for NSW is conducting a cost-benefit analysis on the most effective and efficient speed camera for their area and will also develop protocols for the operation of the speed cameras, including regular review and report of their functionality. Moreover in NSW, the preferred enforcement method is via high visibility policing.

Alongside their demerits system, NSW has a positive reinforcement program, the Fair Go for Safer Drivers Initiative, which started in 2012. It offers drivers discounts on license renewal fees for maintaining a good driving record. There is evidence of its success but is considered insufficiently marketed to reach its full potential. Within the demerit system, NSW is assessing the impact of increasing community acceptance of low-level speeding within the context of changes to the points system. NSW is

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[2] NSW Centre for Road Safety (2011). *NSW Speed Zoning Guidelines*. North Syndey, NSW; NSW Transport Roads & Traffic Authority. Available here: https://roadsafety.transport.nsw.gov.au/downloads/nsw_sza.pdf

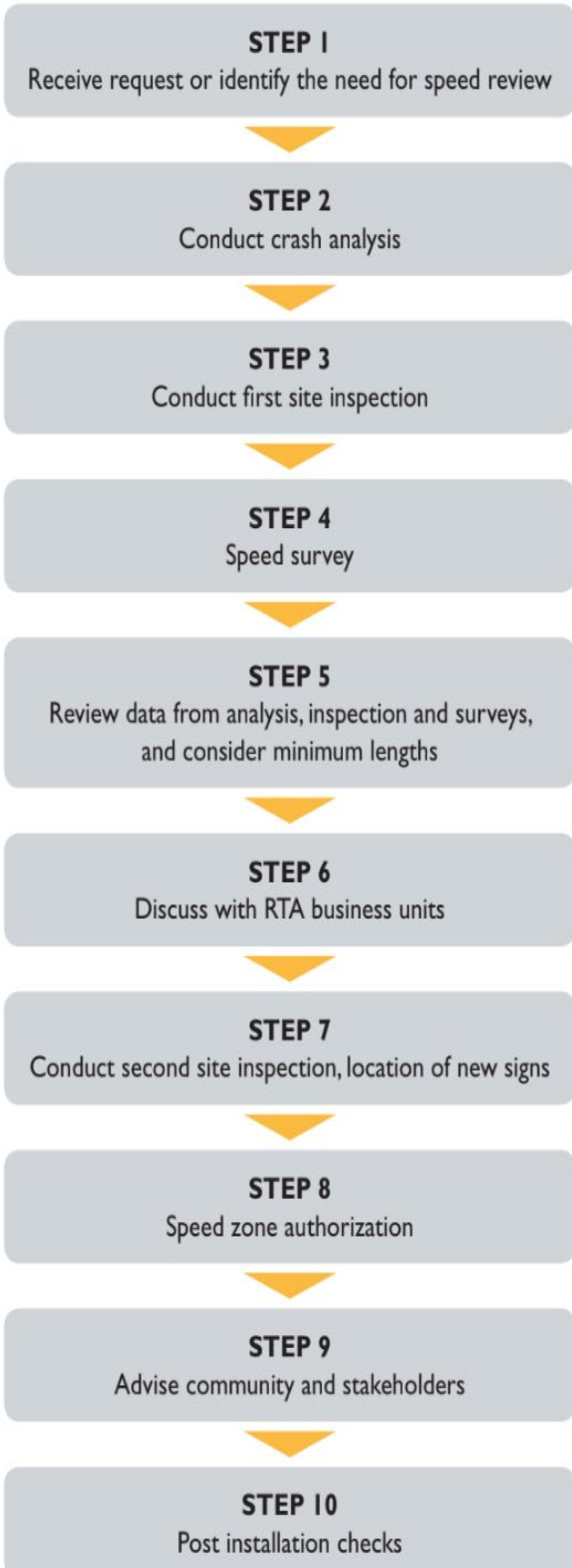
[3] Joint Standing Committee on Road Safety (2014). *Speed zoning and its impact on the Demerit Points Scheme*. New South Wales Parliament.

more lenient that other jurisdictions in Australia and the overall lack of uniformity makes it challenging to establish a nationally consistent system.

Speeding is involved in 40% of road fatalities and 16% of injuries each year in NSW. Speed zone guidelines help drivers recognize the speed limit for the road environment. NSW uses several types of speed signage, including regulatory speed limit, advisory speed limit, and speed restriction ahead sign. NSW considers a route based approach that ensures speed limit changes on a route facilitate mobility while reducing the number changes in speed.

Key factors in setting speed limits in NSW include: roadway function, roadside development, road characteristics, traffic characteristics, at-risk locations. RTA is responsible for setting and reviewing speed limits in NSW; they use a 10-step process seen below:

FIGURE 2.4 SPEED ZONE REVIEW PROCEDURE



High casualty rates or concentrations are indicators of safety deficiencies. However, it's important to investigate if clusters of crashes suggest a localized problem that would be better treated through engineering treatments.

NSW uses a 50 km/h default urban speed limit, increasing to 60 km/h on major arterial roads. A speed limit of 70 km/h and 80 km/h may be applied but requires restricted abutting access and low to no pedestrian activity. Higher speeds are restricted to motorways and top out at 110 km/h. Shared zones are restricted to 10 km/h while school zones and other areas with high pedestrian traffic or local traffic are restricted to 40 km/h. Work zones also have reduced speed limits. NSW uses variable speed limits which adapt to changes in traffic management and incident responses, weather, and roadwork. NSW recommends against buffer zones (transitional zones) in changing speed limits and prefers "speed restriction ahead" signage to reduce the numbers of speed limit changes. NSW developed a tool to support decision making. The United States' FHWA has adapted this tool for their needs as USLIMITS2.

Recent National Speed Management Developments

Speed management is a cornerstone to all transportation safety planning. The MUTCD recommends using the 85th percentile to set speed limits, but the National Transportation Safety Board found that relying on the 85th percentile speed to change speed limits in high speed zones results in "higher operating speeds and new, higher 85th percentiles in the speed zones, and an increase in operating speeds outside the speed zones."[4] The National Committee on Uniform Traffic Control Devices (NCUTCD) acknowledges the limitations of the 85th percentile but restrict their recommendations to more research is needed and policy statements should be left to guideline documents rather than changes to the MUTCD.[5]

In line with a recent NTSB Safety Study 17/01 that recommended incorporating the Safe Systems approach for urban roads to strength protection for vulnerable users, states across the United States are adopting speed limit setting laws that give cities more flexibility and cities are leveraging these tools to make safety improvements.

Massachusetts sought to give greater local authority in setting speed limits. MGL c. 90 § 17C allows "thickly settled" cities and towns to adopt a 25 mph default speed limit by ordinance for all non-state-owned streets. Cities and towns can also set 20 mph safety zones, which they can use their own criteria to create.

- In 2016, Cambridge lowered speed limits to 25 mph citywide and began implementing 20 mph safety zones later that same year.
- In 2017, Boston reduced the default speed limit from 30mph to 25 mph and communicated this reduction through ads, social media, and traditional media. The Insurance Institute of Highway Safety found that the estimated odds of a vehicle exceeding 35 mph fell 29.3%, the estimated

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[4] National Transportation Safety Board. (2017). *Reducing Speeding-Related Crashes Involving Passenger Vehicles.* Safety Study NTSB/SS-17/01. Washington, DC

[5] https://ncutcd.org/wp-content/uploads/meetings/2019A/AttachNo12.18B-RW-03.SpeedLimitProcdedures.Approved.pdf

odds of a vehicle exceeding 30 mph fell 8.5%, and the estimated odds of a vehicle exceeding 25 mph fell 2.9%.[6]

Washington State has two pieces of enabling legislation that, together, allow cities to set safe speed limits. RCW 46.61.415 - When local authorities may establish or alter maximum limits allows local agencies to establish/alter maximum limits on local streets. WAC 468-95-045 is a modification to the State MUTCD that provides local jurisdictions with considerations about what requirements they need to meet revise the posted speed limit.

- In 2016, the Seattle City Council passed an ordinance to lower the speed limit from 25 to 20 mph on 2,400 miles of neighborhood streets and the default speed limit from 30 to 25 mph on arterials. To make their case for lower speed limits, Seattle DOT (SDOT) staff compiled two documents. The first was a detailed history of the city's 1934 decision to reduce speed limits to 25 mph on arterials and 20 mph on residential streets, and their 1948 decision to raise the default maximum speed across the city from 25 to 30 mph. The second was a data-based justification for lower speed limits in 2016. In this document, SDOT made the case that the built environment, the city's Vision Zero commitment, and recent mode shift away from driving and toward walking, biking, and taking transit all signaled a need for lower, safer speed limits. SDOT also included speed and safety data from all of their recent Vision Zero pilot projects.

  Since the law passed, SDOT has built on the momentum of reducing speed limits across the city to leverage existing state-level authority to reduce speed limits on 3 high crash corridors using a context-sensitive engineering study. They are also leveraging both of these tools to reduce speed limits at a neighborhood scale in particular zones.

Oregon (Senate Bill 558) allows all cities in the state to establish a 20 mph speed limit on all non-arterial streets in residence districts under city jurisdiction.

- In 2017, Portland was given the authority to lower residential speed limits from 25 to 20mph. In 2019, the Legislature expanded this to all cities.

  Portland also has permission to use an "alternative method" for non-arterial streets that references the 85th percentile speeds but places greater emphasis on vulnerable users and the risk of a future crash. Locations where this alternative method is used will require an evaluation report after a two-year trial period focusing on the changes in the number of injury and fatal crashes. This methodology was approved in 2016 and the experimental period was extended to four-years to account for crash data report lag time.

Minnesota Statute (Section 169.14, Subd. 5h - Speed limits on city streets) allows cities to establish speed limits on city streets without conducting an engineering and traffic study. Any city that uses this authority must also develop procedures to set speed limits based on national urban speed limit guidance

[6] Hu, Wen and Cicchino, Jessica B. (August 2018). Lowering the Speed Limit from 30 to 25 mph in Boston: Effects on Vehicle Speeds. Insurance Institute for Highway Safety. Arlington, VA.

and local crash history. The statute went into effect August 1, 2019 and it's unclear if any city has made changes yet.

In 2014, the **New York** State Legislature passed a bill lowering citywide speed limits from 30 to 25mph in New York City. Prior to this, family members of people killed in traffic crashes in New York campaigned with City Council members and local agencies to reduce the citywide speed limit. As New York City rolled out its Vision Zero campaign, the Action Plan called for City Hall to lead a campaign to reduce the citywide speed limit to 25 mph and for the Department of Transportation to create 25 mph arterial slow zones on dangerous arterials.

The State Legislature also granted permission to establish an automated speed enforcement program involving cameras located in school zones. In 2019, having lowered speeding by over 60 percent in camera locations, the City obtained new authority to expand this program from 140 to 750 zones.

New York City created numerous Neighborhood Slow Zones across the five boroughs in response to applications from communities. They generally include 20 mph on-street markings, signs, speed humps, and other traffic calming treatments. Neighborhood Slow Zones are typically small (about ¼ square mile) residential areas with low traffic volumes and minimal through traffic.

6 Additional Opportunities to Improve Road User Safety

6.1 Engineering interventions to slow vehicles and improve safety for vulnerable road users

By Dillon Fitch, Sonia Anthoine, Bingchu Chen, Salvador Grover

Introduction

Drivers are likely to choose speeds by categorizing roads based on their appearance and their adjacent land use (Charlton and Starkey, 2017). These categories are driven by psychological parameters such as perceptions, cognition, and memory, but also arise from complex behavior/environment interactions (Bucchi et al., 2012). When drivers choose speeds that are unsafe (for themselves or for vulnerable road users), transportation engineers can attempt to alter road environments to try and slow drivers (known as traffic calming). From a psychological perspective, traffic calming interventions are simply ways in which engineers attempt to increase the visual/cognitive workload of the driver for them to naturally reduce their speed. This increase in visual/cognitive workload can be achieved through several design interventions. While the reduction in vehicle speeds provide clear safety benefits (see prior section), many of the downstream safety benefits are not covered in this section. Below we list a small set of these interventions and synthesize the expected effects on driver speed and vulnerable user safety so they can be compared to other non-engineering interventions.

Traffic Calming Interventions

Speed bumps, humps, tables, and other similar interventions use the concept of vertical vehicle deflection to slow cars. By forcing vehicles up and over physical bumps, drivers naturally slow to keep control over their car. Current speed profiles and road context are important for deciding on an appropriate vertical deflection intervention and an expected speed reduction. Studies in Denmark and the United States have shown that the installation of a single speed bump reduced average speeds by 2.7 to 3.4 mph (Agerholm et al., 2017; Cottrell et al., 2006). Another American study found that installing multiple speed bumps in succession can reduce average speeds by 8 to 12 mph in some areas (Ponnaluri and Groce, 2005).

Chicanes and lane shifts use horizontal deflection to slow vehicles. Chicanes have been found to reduce average speed by 1.3 to 3.2 mph (Agerholm et al., 2017; Kacprzak and Solowczuk, 2019; Lantieri et al., 2015). Some European studies have also found that chicanes reduce average speeds, but that these reductions depend greatly on chicane design (i.e. the degree of deflection and the view of the road beyond the chicane) as well as the presence of other traffic-calming features (Barbosa et al., 2000; Kacprzak and Solowczuk, 2019; Lantieri et al., 2015).

Medians separate opposing lanes of traffic on divided roadways. In Sweden, roads redesigned with median barriers had an 80 percent reduction in fatalities (Johansson, 2009). On the contrary, suburban roads in Texas (30-45mph) saw median presence resulted in higher speeds than when a median was not present (Fitzpatrick et al., 2001). The effect of median installation on driver speed is likely heavily dependent on context.

Road diets (lane reduction) are commonly used to change four-lane arterials to a two plus one (center turn lane) while adding bike infrastructure. Most studies demonstrate widespread safety benefits for road diets (four lanes to two plus one) (Lyles et al., 2012; Thomas, 2013). The expected effects of a road diet are reductions of speed between 2 and 5 mph with greatest reductions from the fastest drivers (although a few studies show slight increases in speed after road diets), and between 19 and 47 percent reduction in crashes (Thomas, 2013).

Lane narrowing involves intentionally reducing the width of traffic lanes to slow traffic. This has reduced speeds by 1.4 to 4.9 mph in some contexts (Gross et al., 2009; Solowczuk and Kacprzak, 2019). In simulation, narrowing lanes have showed speed reductions of 1.4 mph per 1.6 foot reduction in lane width (Godley et al., 2004).

Roundabouts have been found to reduce the speed of vehicles at intersections (Jensen, 2017) and have consistently shown to reduce all crashes in all intersection contexts in the range of 35-76% in the United States (Littell et al., 2006). However, more recent evidence suggests that safety for bicyclists may be more mixed (Jensen, 2017; Kullgren et al., 2019; Turner et al., 2019). The mixed effects of roundabouts on bicyclist safety is likely due to the importance of design details. For example, multilane roundabouts are more commonly found to reduce bicyclist safety compared to single lane roundabouts (DiGioia et al., 2017; Reynolds et al., 2009).

On-street parking increases the uncertainty and potential risk associated with traveling by any mode (Edquist et al., 2012). However, drivers adapt to parked cars and some studies show that in low speed roads, high parking densities correlate with slower speeds (Daisa and Peers, 1997) and fewer severe and fatal crashes (Marshall et al., 2008). Given the mixed evidence, road context is likely to strongly moderate any effects of on-street parking on speed and safety.

Building setbacks have been found to affect speed on urban roads (Edquist et al., 2012), where small setbacks roads show a mean free-flow speed of approximately 1.5 mph less than comparable roads with large setbacks (Marshall et al., 2008). Although setbacks are not usually under the purview of transportation engineers and thus not normally considered a traffic calming mechanism, their effects highlight the need for coordinating zoning codes with road user safety.

Bicycle focused interventions

Few studies investigate the effect of bicycle infrastructure on vehicle speeds. Some studies describe the need to combine bike infrastructure and speed calming measures (discussed above), along with enforcement and changes to culpability laws to maximize cyclist safety (Alluri et al., 2017; Leden et al., 2006; Morrison et al., 2019).

Intersections are found to be the most dangerous areas for the safety of bicyclists. While conclusions on intersection treatments are mixed (Alluri et al., 2017; DiGioia et al., 2017; Reynolds et al., 2009), fewer crashes occurring at intersections where separated bicycle path approaches are deflected 6 to 16 feet away from the main road (Kondo et al., 2018; Schepers et al., 2011).

Current studies that exist on the effects of bicycle infrastructure on safety are also mixed. In some studies, the use of color and high quality markings seem to have an adverse effect on bicyclist safety (Schepers et al., 2011). Some studies conclude that bicycle lanes increase safety (Chen et al., 2012; Kondo et al., 2018;

Kullgren et al., 2019) while others find they decrease safety (Alluri et al., 2017; DiGioia et al., 2017; Jensen, 2008; Meuleners et al., 2019; Reynolds et al., 2009). Other mixed safety outcomes are observed for bicycle crossings, bicycle boxes, separated medians, and lane width changes (Alluri et al., 2017; Chen et al., 2012; DiGioia et al., 2017; Jensen, 2008; Kim et al., 2012; Meuleners et al., 2019; Reynolds et al., 2009; Turner et al., 2011). While evidence is mixed for many bike focused interventions, protected bike lanes and bike boulevards more consistently show increases in bicyclist safety (DiGioia et al., 2017; Marshall and Ferenchak, 2019; Reynolds et al., 2009; Teschke et al., 2012).

Pedestrian focused interventions

Besides the traffic calming interventions above, the link between pedestrian focused interventions and vehicle speed is not commonly reported in the primary literature. So while pedestrian interventions typically focus on reducing vehicle speed, reducing pedestrian exposure, and increasing visibility, most studies focus only on crash and injury outcomes (Elvik, 2009; Peden et al., 2004; Retting et al., 2003; Zegeer and Bushell, 2012). Many studies find that engineering changes are the most effective interventions at reducing pedestrian injury and fatality rates (Grundy et al., 2009; Mutabazi, 2010; Stoker et al., 2015). Highly effective treatments include single-lane roundabouts, exclusive pedestrian signal phasing, curb extensions, pedestrian refuge islands, and pedestrian plazas (Kang, 2019; Retting et al., 2003). These treatments have been found to reduce pedestrian-vehicle crashes by 40 to 70% (Kang, 2019; Retting et al., 2003).

Poor visibility is one of the greatest risk factors for pedestrians - In the US, more than 60 percent of all fatal vehicle-pedestrian collisions occur in low lighting (Stoker et al., 2015). It is commonly accepted that there is an inverse relationship between pedestrian fatalities and roadway and adjacent-to-roadway illumination (Griswold et al., 2011; Sullivan and Flannagan, 2002), however expected effects of adding pedestrian lighting are hard to synthesize due to a wide range of experimentation.

Conclusions

In this synthesis we were not able to review the myriad of engineering interventions that are currently used to slow vehicles and protect vulnerable road users. Instead, we highlighted some key interventions and provided a synthesis of the expected effects of these interventions to allow a magnatude comparison between engineering-based and non-engineering-based interventions. Extensive reviews are available for evaluations of many more interventions (Brown et al., 2017; Campbell et al., 2004).

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6.2 Road and vehicle design improvements to improve safety

By Offer Grembek

Road design and operations

Practitioners are constantly faced with the need to identify effective safety countermeasures. While the implementation depends on the context at the actual location, there is a need to have a research-based baseline to quantify the expected effectiveness of a countermeasure. One commonly method to achieve that is using crash modification factors (CMF).

A CMF is an estimate of the change in crashes expected after implementation of a countermeasure. CMFs are applied to the estimated crashes without treatment to compute the estimated crashes with treatment. A CMF less than 1.0 indicates that a treatment has the potential to reduce crashes, while a CMF greater than 1.0 indicates that a treatment has the potential to increase crashes. The FHWA CMF Clearinghouse is a web-based database of CMFs along with supporting documentation to help users identify the most appropriate countermeasure for their safety needs. The CMF Clearinghouse contains more than 3,000 CMFs for various design and operational features and also provides detailed information for each CMF to help users identify applicable scenarios and the related quality of the CMF. The most applicable CMF should be listed for each countermeasure along with the standard error (if available) and applicable crash types and severities.

In a preliminary effort to identify the most pertinent crash types for California we have generated some descriptive crash statistics for California. While this basic analysis is only an initial effort and not an in-depth more compressive analysis desired, it is a good first step to flag crashes of interest across the state and a set of countermeasures that can help alleviate such crashes. The guiding principle for this analysis were that fatal and severe crashes are the remediation highest priority. To this end, the police reported injury crashes from California for 2014-2018 were collected from the Statewide Integrated Traffic Records System (SWITRS). Using this data the proportion of fatal and severe crashes as part of the total number of reported injury crashes was calculated for crash types. The crash types were based on a combination of two coded crash variables “Type of Collision” and “Primary Collison Factor Violation Category”. This was done across three different types of road users: vehicles, pedestrians, and bicyclists. In an effort to limit the focus to common crash types, the calculation of the fatal and severe proportion was only executed for crash types that meet a certain frequency as specified for each table below. By applying this logic, we are able to identify a preliminary list dominant fatal and severe crash types.

Table 1. Documentation of Proven Countermeasures by NHTSA and FHWA

Crash type	**Fatal & Severe (FS)**	**All injuries (A)**	**FS/A (%)**
Head-On (DUI)	1421	5577	0.2548
Overturned (DUI)	1011	4308	0.2347
Head-On (Wrong Side)	1282	5635	0.2275
Hit Object (DUI)	4865	23549	0.2066

Broadside (DUI)	1194	7361	0.1622

As demonstrated in Table 1, a large number of fatal and severe crashes are head on or overturned vehicles. Some of these can be alleviated by better road design features that provide better road side barriers and better separation from head on traffic. The CMF clearinghouse can provides a list of quality CMF's that are expected to reduce such crash.

A wide and varied range of highway engineering features are also effective in speed management, including surface treatments, dynamic and static signage, and roundabouts (FHWA, 2018b). Highway engineering features that are effective in speed management include:

- Vertical Deflections Within the Roadway (e.g., speed bumps)
- Horizontal Deflections/Roadway Narrowing (e.g., bulb outs, chicanes, center islands, lane narrowing)
- Surface Treatments and Markings (e.g., rumble strips, transverse bars)
- Vertical Delineation (e.g., landscaped medians)
- Dynamic Signing (e.g., speed activated speed limit signs, speed activated warning signs)
- Static Signing (chevron signs)
- Intersection Treatments (roundabouts)
- Gateway Entrance Treatments (to reduce entry speed into communities)

These examples are just a few of the proven countermeasures too numerous to be listed in this report. However, detailed descriptions of these countermeasures are maintained by NHTSA, FHWA, and CDC (Table 2). The sources listed in Table 2 describe conditions under which various countermeasures might be deployed and ratings of expected effectiveness. Crash modification factors (CMF) (i.e., percentage of crashes reduced with implementation), are listed for many of the countermeasures, and such factors can be used to calculate cost-benefit estimates. The documents demonstrate that continued application of currently available proven countermeasures can extend the decades-long trends toward greater road safety.

There are few universal estimates of cost savings if sets of countermeasures were administered on a national scale—however, AAFTS issued a report in 2017 (AAAFTS, 2017) that projects the costs and benefits of meeting current infrastructure needs on a nationwide basis:

> "Cost-effective infrastructure investments (i.e., those for which the benefits exceed the costs) represent an opportunity to improve safety on U.S. highways and streets. This report makes a conservative estimate of such current infrastructure improvement needs. The estimates developed in this report indicate that current infrastructure improvement needs in the U.S. for the roadway types and functional classes listed above would cost $146 billion to address. If all of these needs were addressed, the present value of the 20-year safety benefits would be $348 billion, with a benefit-cost ratio of 2.4. In other words, benefits of $2.40 could be achieved for every $1.00 spent on infrastructure improvement. Addressing these needs could reduce 63,700 fatalities and more than 350,000 serious injuries over 20 years." (AAAFTS, 2017, Page 2)."

Table 2. Documentation of Proven Countermeasures by NHTSA and FHWA

Countermeasure Documentation	**Brief Description**
Countermeasures that work: A highway safety countermeasure guide for State Highway Safety Offices. National Highway Traffic Safety Administration (NHTSA). (Richard et al., 2018). Web Link: NHTSA Countermeasures that Work	The guide is a basic reference to assist State Highway Safety Offices (SHSOs) in selecting effective, evidence based countermeasures for traffic safety problem areas. "The guide describes major strategies and countermeasures that are relevant to SHSOs; summarizes strategy/countermeasure use, effectiveness, costs, and implementation time; and provides references to the most important research summaries and individual studies."
Crash Modification Clearinghouse (University of North Carolina) Web Link: CMF Clearinghouse	"The CMF Clearinghouse User Guide provides information about crash modification factor (CMF) basics for those unfamiliar with CMFs and guidance on how to conduct searches on the CMF Clearinghouse. It also provides advanced tips and functionality for more experienced users."
Office of Safety: Proven Safety Countermeasures, Federal Highway Administration (FHWA, 2017). Web Link: FHWA Proven Countermeasures	"This list of Proven Safety Countermeasures has now reached a total of 20 treatments and strategies that practitioners can implement to successfully address roadway departure, intersection, and pedestrian and bicycle crashes. Among the 20 Proven Safety Countermeasures are several crosscutting strategies that address multiple safety focus areas."

Summary

There is a body of literature that can support practitioners in identifying a set of road design improvements to reduce crashes of all modes.

Vehicle-based road-user protection for vehicle occupants and vulnerable street users

This section considers safety improvements that provide injury protection in a direct or indirect manner. Direct injury protection systems typically serve as a physical barrier that restricts the damage inflicted to the user in an accident. Examples are helmets and restraint systems such as seat-belts and airbags. Indirect injury protection systems typically enhance (or impair) the users' capability to prevent (or cause) a crash, and reduce (or increase) its severity. Some systems enhance visibility (e.g., daytime running lights) or the operational control of a vehicle (e.g., electronic stability control), while other systems impair the operational control of an individual (e.g., childproof doors) [Grembek, 2010].

There are two typical methods to estimate the actual effectiveness of safety measures, before-after studies and cross-sectional studies. In before-after studies we measure safety before the treatment by counting the number of collisions in the 'before' period and then measure again by counting the number of collisions in the 'after' period. If nothing else changed, the difference is attributed to the treatment. However, the traffic environment changes with time. Therefore, we need to compare the safety that would have been experienced in the 'after' period had treatment not been applied, to the expected safety of the treated entity in the after period [Hauer, 1997]. In cross-sectional studies we compare the safety of one group of entities with some common feature to the safety of a different group of entities not having that feature, in order to assess the safety effect of that feature.

An extensive review of published reports and public databases was conducted, to identify relevant information for protection systems that fall within the scope of this effort. Table 3 below summarizes sources that provide information about the effectiveness of vehicle-based user protection improvements.

Table 3. Documentation of Proven Countermeasures by NHTSA, FHWA, and CDC

Countermeasure Documentation	**Brief Description**
Motor Vehicle Safety Web Site, Centers for Disease Control (CDC). Web Link: CDC Motor Vehicle Safety	This web site provides statistics and countermeasures for a number of topic areas, including Child Passenger Safety, Seat Belts, Teen Drivers, Older Adult Drivers, Impaired Driving, Distracted Driving, Pedestrian Safety, Tribal Road Safety, Motorcycle Safety, Bicycle Safety
Elvik, R., Høye, A., Vaa, T. and Sørensen, M. (2009), "Vehicle Design and Protective Devices", The Handbook of Road Safety Measures, Emerald Group Publishing Limited, pp. 543-731	The Handbook of Road Safety Measures gives state-of-the-art summaries of current knowledge regarding the effects of 128 road safety measures. It covers all areas of road safety including: traffic control; vehicle inspection; driver training; publicity campaigns; police enforcement; and, general policy instruments. This section will highlight a sub-set of effective vehicle-based elements that can provide protection to vehicle occupants and non-occupant vulnerable street users.

6.3 Emerging technological opportunities to improve safety

By Offer Grembek

We are heading into an era of improved vehicle and infrastructure technology. The exact trajectory of this era cannot be charted precisely; however, there will almost certainly be major impacts on safety.

A considerable amount of research is beginning to describe the safety benefits of various levels of emerging technology. For example, a recent AAAFTS report (Benson et al., 2018) examines the potential impacts of forward collision warning (FCW), automatic emergency braking (AEB), lane departure warning (LDW), lane keeping assistance (LKA), and blind spot warning (BSW) systems. The report does not attempt to specifically estimate the number of crashes that would be prevented if these technologies were implemented, but provides estimates of the types of crashes, injuries, and fatalities that potentially could be prevented based on the profile of crash types in 2016.

6.4 Other promising policies to improve safety

By Offer Grembek, Aditya Medury, and Ibrahim Itani

Lowering BAC limit from 0.08 to 0.05

Background

One main traffic safety concern is driving after alcohol consumption. In 2016, 33% of traffic fatalities (12,514 fatalities) involved a driver with a blood alcohol level (BAC) above 0.01 g/dL (NHTSA, 2018). The estimated economic impact of alcohol impaired crashes—those involving drivers with illegal BAC levels above 0.08 g/dL—comprised $44 billion of the estimated total of $242 billion caused by all crashes in 2010. These calculations include tangible costs such as property damage, medical bills and increased traffic congestion. This value rises to a staggering $201.1 billion dollars when quality of life valuations are considered (NHTSA, 2017b).

Elevated alcohol levels impact various aspects of driving performance including perception reaction (P-R) time, braking ability, tracking performance, distance estimation, lane deviation and speed variation. P-R time is the duration required for a driver to observe and react to a roadway obstruction. Several studies have examined the effects of elevated BACs on P-R time due to its importance in designing a safe roadway.

Two key national reports (NAS, 2018; NTSB, 2013) have already identified this as a major issue and have generated much debate.

Effect of alcohol on perception and reaction times:

While most of the research indicates that there is significant impairment on perception reaction (P-R) time above 0.08 g/dL, many studies indicate that P-R time starts to deteriorate at much lower BAC levels, including studies suggesting that the deterioration starts at BAC levels of 0.02 g/dL (Moskowitz et al., 2000)

Simple reaction times were found to be impaired at low blood alcohol levels by several studies including those conducted by Wang et al. (1992), which used a visual stimulus (0.047 g/dL), and by Baker et al. (1985), which used auditory and visual stimuli (0.055%).

Choice reaction time was found to be affected by BAC levels as low as 0.02 g/dL for a moving visual stimulus, and 0.04 g/dL for a driving simulator task (Gengo et al., 1990; MacArthur and Sekuler, 1982).

Human laboratory research has shown that BACs above 0.05 g/dl significantly impair performance on some motor tasks such as tracking, tapping, reaction time, and body sway (Mitchell, 1985; for reviews see Eckardt et al., 1998; Finnigan and Hammersley, 1992, Brumback et al, 2007).

Table 1. Consistent Impairment Effects at Different Blood Alcohol Levels (adapted from Moskowitz et al., 2000)

BAC (g/dL)	Consistent Impairment Effect

0.001	Driving Simulator Lane Deviations, Divided Attention
0.01	Drowsiness
0.03	Vigilance
0.04	Perception, Visual Functions
0.05	Tracking
0.06	Cognitive Tasks, Psycomotor Skills, Choice Reaction Time
0.08	Legal limit
0.1	Simple Reaction Time, Critical Flicker Fusion

Epidemiological studies of BAC level on Crash Risk

Using data from crash and control subjects from Long Beach, CA and Fort Lauderdale, FL during 1996-1998, Peck et al. (2008) found that elevated relative risks (RR) were observed for drivers from various age groups when BAC levels reached 0.05% or higher. Among drivers 21 and over the risk of being in a crash started increasing at a BAC of 0.05% (RR = 1.07), and those risks continued to increase at 0.08% (RR = 1.64) and 0.10% (RR = 2.43) but on a less steep curve than for drivers under 21.

Lacey et al. (2016) conducted a case-control study in Virginia Beach, Virginia, that estimated how a driver's use of alcohol, drugs, or a combination of the two contributed to crash risk. Biological samples were collected from more than 3,000 drivers from local crash scenes (cases) and 6,000 non- crash drivers (controls) matched 1 week later according to the time and location of the initial crash. Drivers were found to be 2.07 more likely to be involved in a crash if they had a BAC of 0.05% when compared to controls, and drivers who had a BAC of 0.08% were 3.93 times more likely to be involved in a crash.

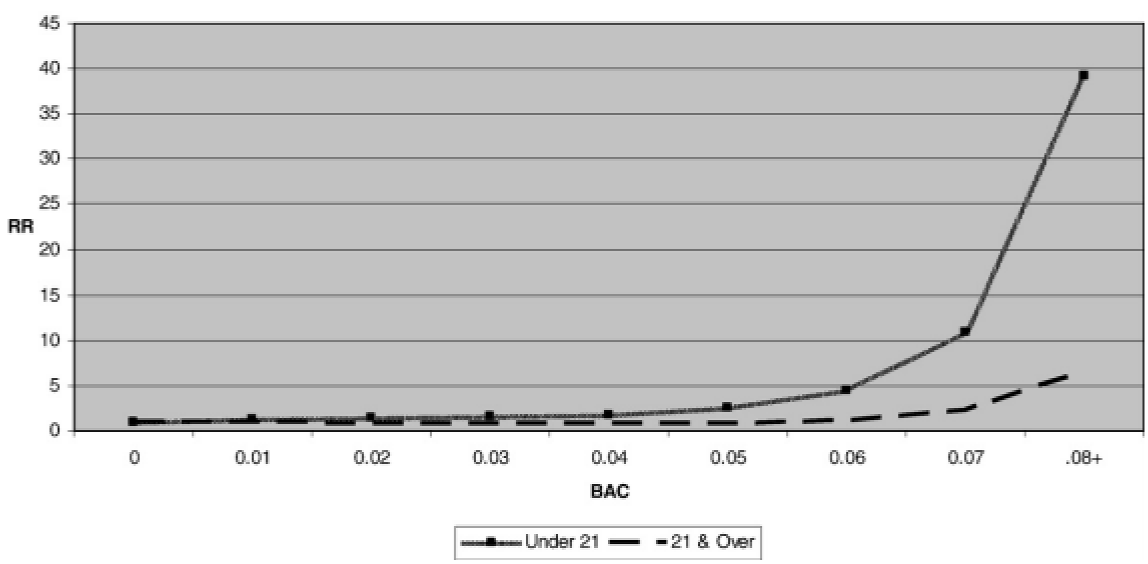


Figure 1. Relative Crash Risk by Driver BAC Level and Age (source: Peck et al (2008))

Effect of lowering BAC level on alcohol-related traffic crashes:

Albalate (2008) evaluated the effectiveness of lowering the BAC limit to 0.05% in eight European countries that changed their policies between 1991 and 2003 and found that lowering the BAC limit to 0.05% was effective in reducing fatality rates (per million people) by 4.3% and reducing fatality rates/km by 6.1%.

In 1991, Australian Capital Territory changed BAC level from .08% to .05%, and Brooks and Zaal (1993) estimated that there was 41% less incidence of drink-driving at BAC above 0.15%, and a reduction of about 90% in drink-driving at BAC between 0.05% and 0.08%. Post-crash data showed 35% fewer drivers with BAC above 0.10%.

Nagata et al (2008) estimated that the rate of alcohol-related traffic fatalities per billion kilometers driven decreased by 38% in the post-law period after Japan reduced BAC from 0.05% to 0.03% in June 2002.

Eisenberg (2003) used a large panel of annual state-level data covering the period 1982–2000 for U.S. states to assess the impact of lowering BAC level to 0.08 and found a reduction of 3.1% in fatal crash rate (per 10,000 drivers).

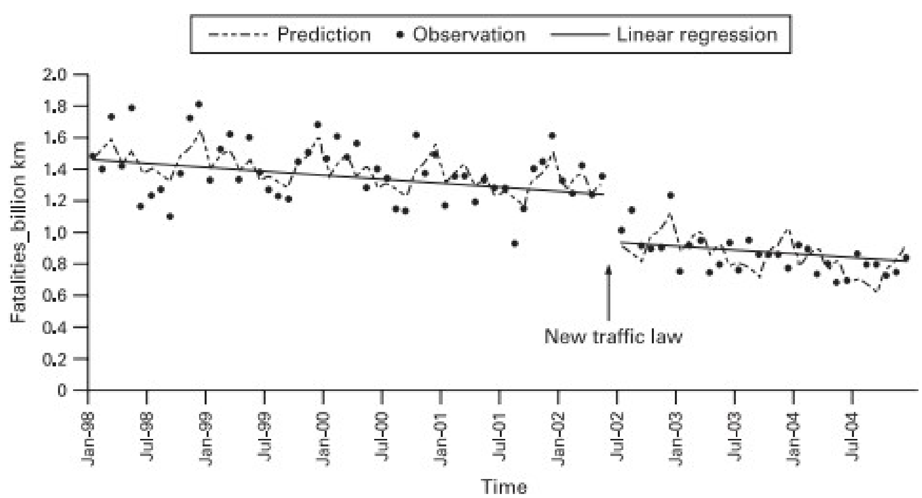


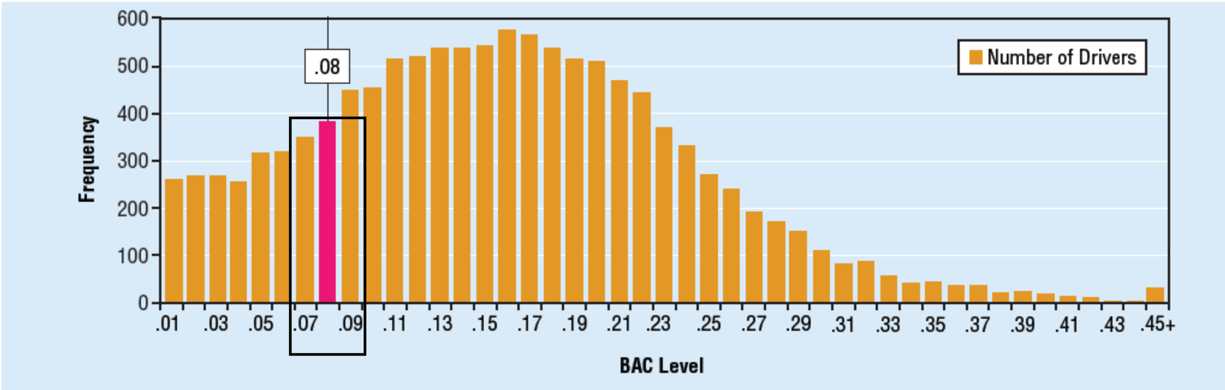
Figure 2. Alcohol-related traffic fatalities (per billion km driven) in Japan (Source: Nagata et al (2008)

Burden on traffic safety:

In 2017, 29% of traffic fatalities in the United States (and 31% of all fatalities in California), involved a driver with a blood alcohol level (BAC) above 0.08 g/dL (NHTSA, 2018).

Among fatalities with drivers with BAC level above 0.01 g/dL, 5% of traffic fatalities nationally and in California occurred between the ranges of 0.05-0.079 g/dL.

Distribution of BACs for Drivers With BACs of .01 g/dL or Higher Involved in Fatal Crashes, 2016



Source: FARS 2016 ARF

BAC Limits worldwide

Most countries in Europe have establish BAC limits of 0.05 g/dL or less. Globally, many other countries have BAC limits that are less than 0.08 g/dL.

	Standard	Commercial drivers	Novice drivers
Austria	0.5	0.1	0.1
Belgium	0.5	0.2	0.5
Bulgaria	0.5	0.5	0.5
Croatia	0.5	0.0	0.0
Cyprus	0.5	0.2	0.2
Czech Republic	0.0	0.0	0.0
Denmark	0.5	0.5	0.5
Estonia	0.2	0.2	0.2
Finland	0.5	0.5	0.5
France	0.5	0.5 (0.2 bus drivers)	0.2
Germany	0.5	0.0	0.0
Greece	0.5	0.2	0.2
Hungary	0.0	0.0	0.0
Ireland	0.5	0.2	0.2
Italy	0.5	0.0	0.0
Latvia	0.5	0.5	0.2
Lithuania	0.4	0.0	0.0
Luxembourg	0.5	0.2	0.2
Malta	0.5	0.2	0.2
Netherlands	0.5	0.5	0.2
Poland	0.2	0.2	0.2
Portugal	0.5	0.2	0.2
Romania	0.0	0.0	0.0
Slovakia	0.0	0.0	0.0
Slovenia	0.5	0.0	0.0
Spain	0.5	0.3	0.3
Sweden	0.2	0.2	0.2
UK [i]	0.8	0.8	0.8
Switzerland	0.5	0.1	0.1

Roadway design considerations

The diminished performance is not accounted for in perception reaction time assumptions in current design standards and could render parts of the transportation system unsafe (Itani and Grembek, in preparation).

According to the AASHTO code (2001), safe stopping sight distance is an integral factor in roadway design. Perception reaction time is used in determining the minimum required stopping sight distance at different speeds. Sight distance factors into roadway design via several features including turning radii and grades. The AASHTO code uses a P-R time of 2.5 seconds in sight distance calculations to determine brake reaction distance. Brake reaction distance is the distance travelled by a driver during the time between exposure to stimulus and when the driver applies the brake. Simple unexpected reaction tasks require 1.5 seconds, while more complex tasks require 2.5 seconds—the 2.5 seconds exceeds the 90th percentile required brake reaction time (Johansson and Rumar, 1971).

Considering the typical speed limit of 70 mph on many U.S. highways, the currently required stopping sight distance is 730 ft. One study indicates that the increase in P-R time could be as significant as 17% for a blood alcohol level of 0.08 g/dL (Moskowitz et al. 2000). If the required P-R time increases by 17%, the required stopping sight distance is increased by 41.3 ft. Therefore, for a constant sight distance, this increase in P-R time requires a decrease in the speed limit. While many roads are designed to provide more than the minimum required stopping sight distance, the factor of stopping sight distance may be the limiting design element for some roadways. Thus, some roads that are currently considered safe may actually be deemed unsafe when this potential increase in P- R time is taken into account (Itani and Grembek, in preparation).

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