HUMAN FACTORS, SAFETY AND THE IMPACTS OF SPEED

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ABSTRACT

Speed is a divisive issue not just for the public but for the traffic engineering community as well. On the one hand faster speeds are viewed as a positive attribute of the road network, suggesting that mobility is optimized and efficiencies are at their peak. On the other hand, faster speeds are seen as detrimental to road safety, and an attribute of the system that creates a barrier to comfortable and safe movement for pedestrians and cyclists. The conventional wisdom concerning the relationship between speed and crash risk has been somewhat fractured, and this in part has fuelled the burning debate concerning speed, and establishing speed limits and target operating speeds.

While the traffic engineering community has consistently concurred that crash severity increases as operating speeds increase, the community is less agreeable concerning the effect of operating speed on crash probability/occurrence. For a long time, traffic professionals have advocated that the probability of a crash follows a U-shaped curve, where excessively low and exceedingly high speeds have higher crash probabilities than moderate operating speeds. The most recent, and statistically robust, research has indicated that this long held belief concerning speed and crash risk is not valid, and that crash probability also increases with operating speed.

The purpose of this paper is to articulate the speed and crash relationship by presenting the statistical evidence from the available research. In addition to the direct examination of correlation between speed and crash risk, the paper will also examine some of the impacts that operating speed has on road user behaviour, and how these impacts help establish the causal relationship between speed and safety.

INTRODUCTION

In 1885 Karl Benz unveiled the first gasoline-powered automobile – the fastest his car could operate was about 20 km/h (1). Since that time advances in engineering and science have produced faster vehicles and better roads, both of which have resulted vast increases in automobile travel speeds. Today, attainable speeds and the maximum speed shown on the speedometers of most motor vehicles exceed the maximum legal speed limits on most roads.

At present, *speeding*[1] is deemed to be a primary factor in crash causation across the globe. According to a multi-country survey concerning road safety, speeding is the number one road safety problem in many countries, often contributing to as many as one third of fatal crashes and an aggravating factor in most crashes (2). In Canada, over 700 people are killed and more than 3,500 people are seriously injured annually in speed-related crashes (3). In fact, speeding is a factor in about 25% of deaths from vehicle crashes (3).

Canada's current Road Safety Strategy explicitly recognizes that speeding is a key contributing factor in crashes on Canadian roads (4). This suggests that speeding is a significant road safety issue for Canada, and effectively addressing this issue is an important contribution to a better Canadian transportation system. However, in order to effectively address the issue of speed as a road safety

[1] Speeding is defined as exceeding the posted speed limit, or driving too fast for conditions.

issue, it is necessary to have a proper understanding of how speed affects crash risk, and the mechanisms that underscore the relationship.

While the traffic engineering community has come to a consensus that crash severity increases as operating speeds increase, the community is less agreeable concerning the effect of operating speed on crash probability/occurrence. For a long time, traffic professionals have advocated that the probability of a crash follows a U-shaped curve, where excessively low and exceedingly high speeds have higher crash probabilities than moderate operating speeds (see Figure 1). The trouble is the research that produced the U-shaped curve is dated and questionable, yet many practitioners adhere to the theory.

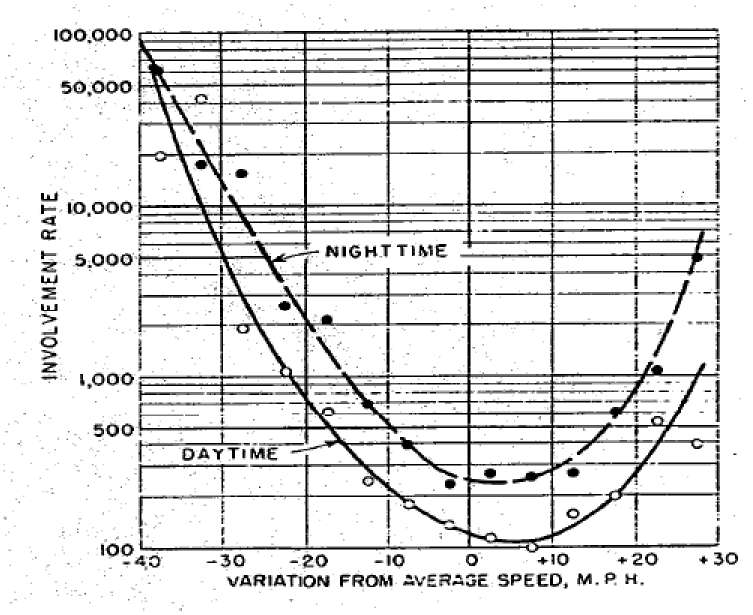

FIGURE 1: Solomon Curve Relating Speed to Crash Risk
(Source: Solomon D (1964) "Accidents on Main Rural Highways Related to Speed, Driver and Vehicle", US Department of Commerce & Bureau of Public Roads, Washington DC.)

The purpose of this paper is to articulate the speed-crash relationship by presenting the statistical evidence from the best available research. In addition to the direct examination of the correlation between speed and crash risk, the paper will also present some of the impacts that operating speed has on road user behaviour, as these impacts help establish the causal relationship between speed and safety.

CRASH AND SPEED RELATIONSHIP

While the laws of physics make it very clear that speed and crash severity are inextricably linked (i.e., severity increases geometrically as speed increases), there has been a good deal of controversy over the impact of speed on crash occurrence. This is primarily because the variety of road design and operating characteristics can obfuscate the precise relationship between speed and crash frequency. This has translated to numerous studies and research efforts on this topic that have presented conflicting results on this important relationship. However, the most recent and statistical robust research on speed and crash occurrence definitively indicates that, all other factors being equal, increased speed also increases crash occurrence (5)(6). The magnitude of the increase is dependent on the specifics of each case with urban areas having the most pronounced relationship, and controlled-access facilities the weakest. The remainder of this section on the correlation between crash risk and speed is based on the meta-analysis and findings from Elvik (6).

For a given roadway type, there is a strong statistical relationship between speed and crash risk for speeds in the range of 25 km/h to 120 km/h. When the mean speed of traffic is reduced, the number of crashes and the severity of injuries will almost always go down. When the mean speed of traffic increases, the number of crashes and the severity of injuries will usually increase. The relationship between mean travel speed and crash risk can be adequately described in terms of the following model:

$$CMF = \left(\frac{V_a}{V_b}\right)^X$$

Where: CMF = Crash modification factor
V_a = Mean speed in the after period
V_b = Mean speed in the before period
x = Statistical constant from Table 1

Table 1: Parameters for the Speed-Crash Risk Model

Crash Severity	Rural roads/freeways: Best Estimate	Rural roads/freeways: 95% Confidence Interval	Urban/residential roads: Best Estimate	Urban/residential roads: 95% Confidence Interval	All roads: Best Estimate	All roads: 95% Confidence Interval
Fatal	4.1	2.9, 5.3	2.6	0.3, 4.9	3.5	2.4, 4.6
Serious Injury	2.6	-2.7, 7.9	1.5	0.9, 2.1	2.0	1.4, 2.6
Slight Injury	1.1	0.0, 2.2	1.0	0.6, 1.4	1.0	0.7, 1.3
Injury	1.6	0.9, 2.3	1.2	0.7, 1.7	1.5	1.2, 1.8
PDO	1.5	0.1, 2.9	0.8	0.1, 1.5	1.0	0.5, 1.5

The relationship between speed and crash risk can to some extent be modified by the road environment, by vehicle-related factors, and by driver behaviour, but the effects of speed on crash risk are remarkably consistent across different contexts.

The above relationship between speed and crash risk is significantly different from the traditional U-shaped relationship that has shaped much of the current North American thinking on speed limits and speed management. The U-shaped relationship between speed and crash risk is questionable for two reasons:

1. The U-shape is generally expected to be an artefact of errors in the measurement of speed (7, 8); 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 (9).

Pedestrian Impacts

The effect of speed on the crash risk of pedestrians, bicyclists, and motorcyclists is more pronounced than crashes involving only motor vehicles as the former group of users is unprotected by crumple zones, seatbelts, and airbags to absorb part of the energy dissipated in the crash. Hence, these road users require special mention.

The probability of a pedestrian being killed in a motor vehicle crash increases dramatically with the impact speed. Results from on-the-scene investigations of collisions involving pedestrians and cars show that 90% of pedestrians survive being hit by a car at speeds of 30 km/h; whereas less than 20% survive at speeds of 50 km/h (see Figure 2). The figure also shows that the impact speed at which a pedestrian has a 50% chance of surviving a crash is around 45 km/h. (10)

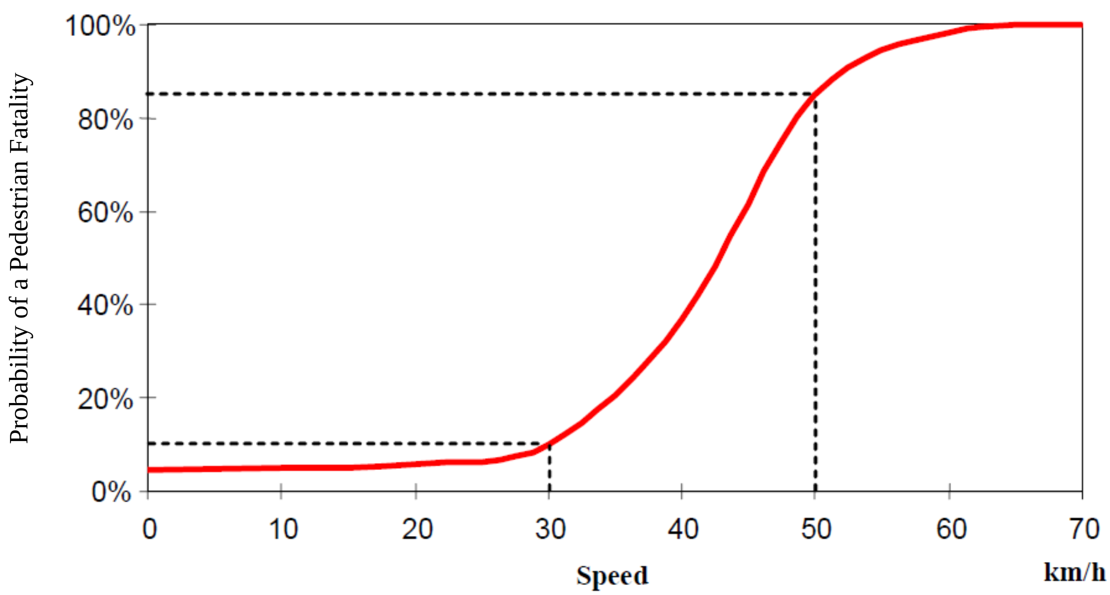

FIGURE 2: Survivability of a Pedestrian in a Motor Vehicle Crash (Source:10)

Motor vehicle speeds create a safety inequity in the road system. The general concept that increased speed increases crash risk pertains primarily to motor vehicle operators as they have the greatest potential to achieve greatly elevated speeds. Since pedestrians have a limited ability to increase their walking speed, absolute increases in motor vehicle speeds increases the speed differential between motorists and pedestrians. This significantly degrades the safety of pedestrians and other vulnerable road users that are exposed to motor vehicle traffic, creating a greater inequity in the safety of the different road users.

THE ETIOLOGY OF SPEED AND CRASHES

A correlation between operating speed and crash risk does not necessarily imply causation. For increased speed to cause an increase in crash risk, as opposed to just being correlated with it, there must be an etiology that is based primarily on driver behaviour and capabilities. It is perhaps obvious but definitely worthy of mention that speed reduces the time/distance available for motorists and other road users to perceive, react and execute avoidance manoeuvres to unfolding situations. In addition, sound research has also determined that speed changes visual perception capabilities of a road user. These links in the causal chain are discussed below. Furthermore, there is some discussion on the speed adaptation phenomenon, and the network level impacts of speed on road safety.

Perception-Reaction Time

At a higher speed the distance travelled during the perception-reaction time of the motorist is increased, leaving less space for manoeuvring to avoid a crash. This is despite any increase in vigilance that could marginally decrease the perception-reaction time for higher speeds. The response time by drivers depends greatly on the type of situation, the degree of urgency, and the speed of the vehicle when the response stimulus is presented.

The main impact of speed on perception-reaction is simply that speed decreases the time available to react to an unfolding event or obstacle. All things being equal, a motorist traveling at a faster speed will travel further during perception phase of the driving task, and will therefore have less time to react to a hazard (see Figure 3). This is particularly troublesome during conditions of low light, as the perception-reaction time is significantly influenced by visibility conditions. Specifically, in low light conditions the distance at which drivers can detect an un-illuminated, un-reflectorized hazard depends on the vehicle headlights, the driver's sensitivity to contrast, and his/her expectation of encountering the hazard. So in conditions of low light, when operating at a high speed, a low-contrast hazard may not be detected in time to start braking. This is exacerbated by a high workload (e.g., traffic merging, reading signs), fatigue, and impairment.

It has been argued that a positive impact of higher speed is an increase in driver vigilance, which in turn leads to lower perception-reaction times. This is true, as the research shows that drivers of higher speed vehicles respond up to 0.5 second faster than those at lower speed under similar conditions. However, the rather nominal decrease in perception reaction time from increased vigilance is not nearly enough to offset the other (negative) impacts that higher speeds have on driver behaviours and capabilities.

In a similar argument for speed being safety positive, it has been suggested that "high design speed" roads offer better forward visibility than other roads, and therefore, a stimulus/object will come into view at a greater distance providing more time for crash avoidance. This is also true, however, in some cases the size of the object and distance to the object when first visible will subtend a small visual angle, making the object difficult to detect or discriminate from the background. Therefore, in some circumstances the perception distance is not significantly increased, and the driver's reaction time is not impacted.

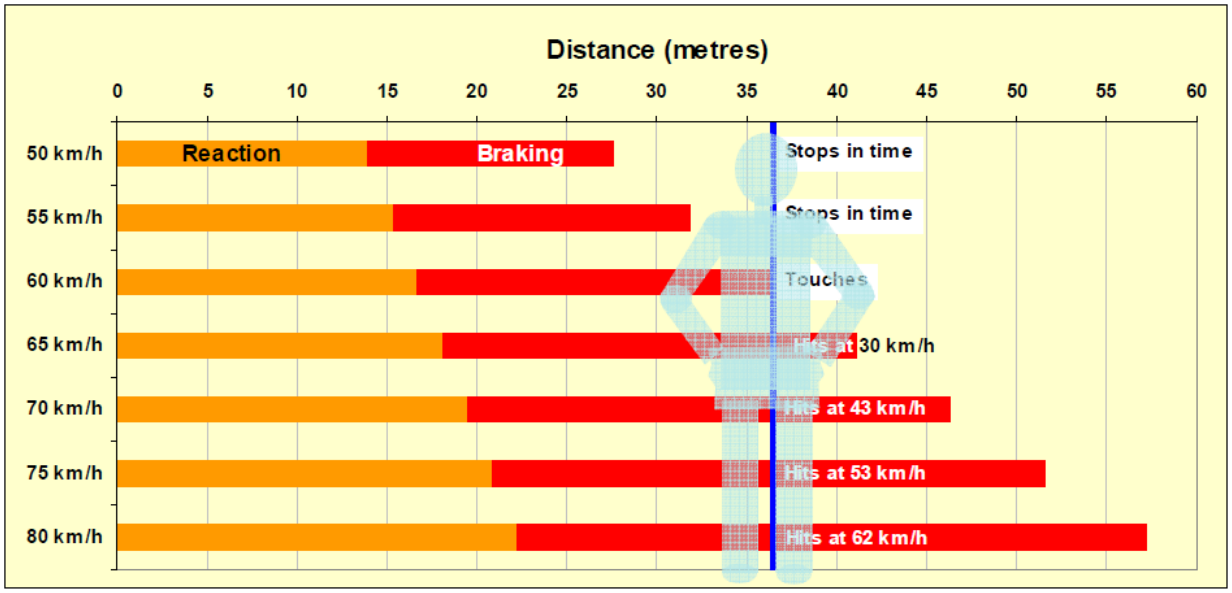

FIGURE 3: Distance Traveled During PRT and Braking Manoeuvres (Source:10)

Manoeuvres and Execution Time

There are two aspects of vehicle manoeuvring that are affected by operating speed.

Firstly, as with perception-reaction time, vehicle manoeuvring takes time, and at higher operating speeds the distance travelled during that manoeuvring time is greater. In the event that the appropriate avoidance manoeuvre is a decrease in speed, the braking distance is proportional to the square of the speed (V^2), hence the distance between pressing the brake and coming to a halt increases greatly with increasing speed (see Figure 3).

Secondly, at high speeds motor vehicles become more difficult to manoeuvre, especially in critical situations when fast action is required to avoid a crash. To start with consider the concept of a controlled lane change manoeuvre in order to avoid an obstacle in the lane ahead. An emergency lane change is much like negotiating a reverse curve, where the quickness with which the lane change is made is dependent on the lateral forces imposed on the driver – how drastically can the driver comfortably turn the steering wheel? What we know from curve driving is that motorists are far more comfortable accepting greater lateral forces at lower speeds. So as operating speed increases, the acceptance of lateral forces decreases, and the time required to complete an emergency lane change manoeuvre increases.

Also, in many instances drivers at higher speeds tend to underestimate the reaction to their steering input and react too violently, causing loss of vehicle control. For example, recovery from a low angle lane departure to a pavement edge drop is more easily accomplished at a low speed than at a high speed. In both situations, the tires scrub against the edge drop, until the front-wheel steer angle is sufficient to overcome the resisting force and to lift the obstructed (scrubbing) front tire over the edge drop off. Once the vehicle mounts the edge drop, the large steering angle creates a "slingshot effect" across the travel lane. The research has generally shown that the ability of a driver to recover from a pavement edge drop is a function of vehicle speed (among other things).

Visual Field

As vehicle speed increases the amount of visual information that is available to process increases dramatically since the visual scene changes at a faster rate. In order to manage the flow of information the motorist eliminates some of the information (because it cannot be processed) by subconsciously narrowing the visual field. When an individual is standing still, the normal visual field is about 180º. As the individual begins to move forward, the field of view gradually decreases. At just 40 km/h, the driver field of vision is almost halved to 100°, and at 100 km/h the field of vision is less than 40°. So speed significantly decreases the capability of the driver to assess hazardous situations that are developing in the periphery (Figure 4). Indeed, as speed increases, vision becomes more concentrated on a single point straight ahead.

Another effect of speed on vision is the point of focus. As speed increases, users need to process information from further downstream in order to make timely decisions on speed and path. This results in the focusing point being shifted farther ahead (see Figure 5), making it more difficult for drivers to notice events and conditions that are occurring directly in front of their vehicles.

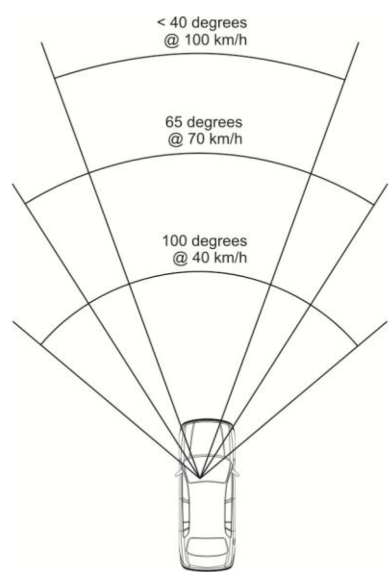

FIGURE 4: The Effect of Speed on the Driver's Cone of Vision

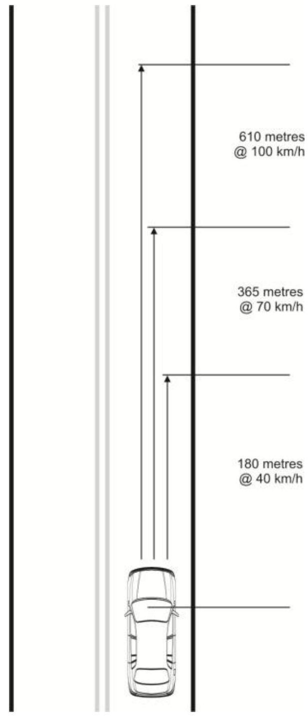

FIGURE 5: Driver Focal Point Related to Operating Speed

The above discussion is not meant to imply that motorists cannot see anything outside of the restricted field-of-view mentioned above. Motorists will shift their gaze through eye and/or head movements to search for and detect objects in the periphery. It is just that the probability of those objects going undetected is increased.

Speed Adaptation

Speed is perceived in relation to a driver's recent average speed. Drivers who have been operating at a high speed for some time, who are required to decrease their speed will tend to underestimate their speed and drive faster than they should. Similarly, a change in the opposite direction causes an overestimate and slower driving. For example, drivers leaving a heavily congested arterial road and entering a free-flowing freeway are likely to enter the mainline at a slower speed than required, because they are adapted to the stop-and-go conditions on the arterial road.

The phenomenon known as speed adaptation – the tendency for motorists to underestimate their travel speeds after having driven for a prolonged period at a significantly higher speed – may cause motorists to travel faster than they should upon entering a curve, an urban area, or other slower speed environment. Researchers have confirmed that during any trip previous driving at a higher speed for an extended period results in motorists having difficulty in adjusting to a lower speed (11)(12)(13).

All motor vehicles have a speedometer to check the driving speed objectively. Nevertheless drivers seem to rely on their own subjective perception or 'feeling' of speed, and this means that higher speeds lead to less safe situations, at high-to-low speed or low-to-high speed transitions.

Effects at Network Level

The main effect of speed at the network level is the concept that “speed creates distance”. The accessibility of goods and services is increased as operating speed increases since greater distances can be covered in the same time, or less time is used to access the same goods and services. In general, all other things being equal, higher operating speeds result in individuals increasing the number of kilometres travelled per unit of time.

In most instances, individuals have a time budget for commute-to-work that is relatively inelastic. What this means is, as operating speeds increase, individuals will relocate further away from their place of employment in order to maintain a constant commute-to-work time. This is most likely because employment centres are usually centrally located in densely populated urban areas with high land/home prices, and having a residence further away from these areas generally means a similar-sized home/property can be purchased for a significantly lower cost.

So in short, higher operating speeds result in urban sprawl, and a significant increase in the number of vehicle-kilometres travelled. With respect to this last metric, there is a meaningful impact on road safety. The usual statistic used to represent the state of the nation concerning road safety is crash risk presented as an exposure-based crash rate (i.e., the number of crashes, injuries, or fatalities per million-vehicle-kilometres travelled). What this means is, as exposure increases, the safety performance of the road system can appear to be improving if the number of crashes increases at a lesser rate. Still, the upshot of this is that the number of crashes has still increased.

THE SPEED-SAFETY PARADOX

What is known about the relationship between certain roadway elements and crash risk is often paradoxical to the relationship between the element and operating speed. The discussion in this paper clearly advocates that a reduction in operating speed produces a reduction in crash risk. However, it is also known that many road modifications that are undertaken to reduce crash risk (e.g., increased lane widths, flatter grades, and larger radius curves) also result in faster operating speeds, thus creating a paradox.

For example, on a two-lane rural road the lane width has a direct relationship with crash risk (i.e., as the lane width decreases, crash risk increases). However, a decrease in lane width is also known to produce a reduction in operating speed. The apparent paradox is the reduction in speed is known to produce a reduction in crash risk, so it is somewhat illogical that an increase in lane width should yield an increase in crash risk ***and*** a decrease in speed.

The same paradoxical relationship holds true for horizontal curve radius, grade, access density and many other elements of the road. As an illustration of the impact consider the example of a horizontal curve on a two-lane rural road with average daily traffic of 12000 vehicles/day, that connects two tangents that are 90 degrees to each other. There are no spirals preceding or following the circular curve.

If the collision prediction model for the facility is:

$$N = 0.004524718 * ADT^{0.5673}$$

Where: N = Number of crashes per annum
ADT = Average daily traffic

Then an ADT of 12000 vehicles will yield an annual crash rate of 0.93 crashes/yr/km. However, the crash rate must be properly adjusted for roadway curvature using the following crash modification factor for a horizontal curve:

$$CMF = \frac{\frac{L_c}{1038.3} + \frac{263.1}{R}}{\frac{L_c}{1038.3}}$$

Where: CMF = Crash modification factor
L_c = Length of curve (m)
R = Radius of curve (m)

The resulting number of crashes on the curve, for a range of curve radii is shown in Figure 5.

Further, if the speed prediction model for the midpoint of the curve is:

$$V85 = 110.386 - \frac{6856.213}{R}$$

Where: V85 = 85th Percentile speed (km/h)
R = Radius of curve (m)

Then, given the parameters for the example, the operating speed and collision risk for curves of different radius are shown in Figure 6. There is clearly a strong and persistent relationship where crash risk decreases as operating speed increases. Furthermore, the relationship is very pronounced on curves with a radius of less than about 200 metres, and both speed and crash risk become fairly inelastic to curve radii above 400 metres.

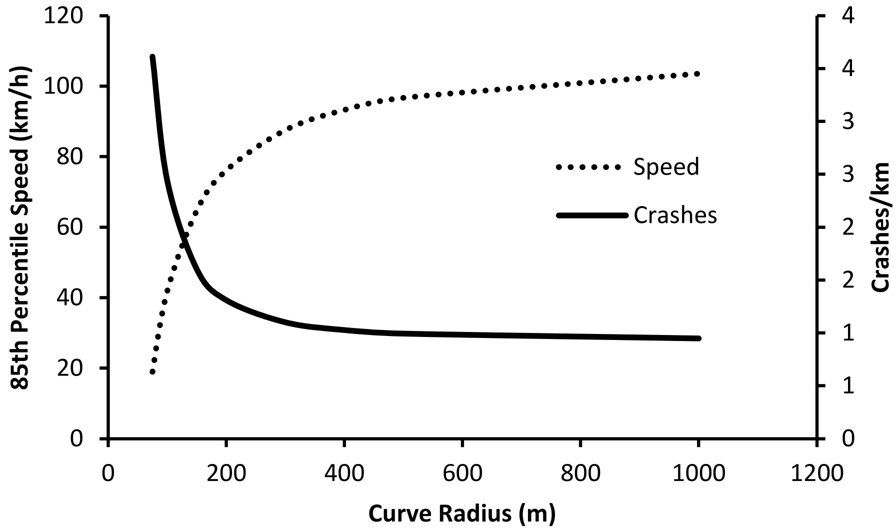

FIGURE 6: Effect of Horizontal Curve Radius on Speed and Crashes

The "lower speed-higher crash risk" paradox is mainly explained by design consistency, or a difference in longitudinal speeds. It is noted that this curve is an isolated curve connecting two fairly lengthy tangents. The operating speed on the tangent section of a typical, two-lane Canadian rural road is about 100 to 115 km/h. As the radius of the curve decreases so does the maximum safe speed for traversing the curve. So the safety gains that may be attributed to the slower operating speed of the curve are massively outweighed by the safety loss resulting from the difference in operating speeds between the curve and the tangent.

The kernel of knowledge from the above illustration is that, despite the relationship between speed and crash risk shown in the speed-crash equation, a reduction in operating speed is not synonymous with a reduction in crash risk. Crash risk is affected by other facets of speed, not the least of which is operating speed consistency, and that speed and safety is not the only relationship that defines the crash risk.

DISCUSSION

Speed and crash risk are directly related – as speed increases so does crash risk. This assertion is based on a statistically robust meta-analysis of speed-crash data from numerous studies, and is remarkably consistent across different road types and contexts. The correlation can be successfully argued as a cause-effect if one considers the impact of elevated speed on distances travelled during perception-reaction-execution, the narrowing of the visual field, and incorrect assessments of self-speed due to speed adaptation.

The fact that speed and crash risk are directly related does not, however, imply that traffic engineering professionals should be reducing operating speeds at every opportunity. While speed can be used as a performance measure for safety, it is also used as a performance measure concerning network operational efficiency. Hence, speed is both a positive and negative force in the transportation network and there is a need for balance. The correct approach to managing speed is most likely to be lowering speeds as much as possible while maintaining reasonable mobility.

For example, a specific instance where speed is a critical element is emergency vehicle response. In this context, speed can save lives. However, while it is desirable to facilitate the movement of ambulances, fire trucks, police cars, and other emergency responders the road system is not easily able to distinguish these types of vehicles from others. Traffic signal pre-emption and rules-of-the-road legislation are techniques that can facilitate emergency response, but permanent physical elements such speed humps and other traffic calming features do not distinguish between vehicle types.

What constitutes reasonable mobility is subjective, and is most likely to be contextual. It is an important policy consideration that must take into consideration all stakeholders in a meaningful way. Nonetheless, speed management is primarily a safety consideration and policy decisions concerning speed should always be safety-centred.

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