Motor Vehicle Speeds: Recommendations for Urban Sustainability

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Abstract

This paper explores how vehicle speeds are related to equitable, environmental and economic sustainability of urban areas. This relationship is manifested primarily through an association between vehicle speeds and road crash casualties, severity of pedestrian crashes, generation of harmful emissions, and relative desirability of neighboring land. Reported research findings describing each of these associations is presented and discussed. Reported experience with implementing various methods of influencing vehicle speeds is then presented and discussed, including automated enforcement, “self-explaining roads”, and in-vehicle systems, among others. In order to support increasing sustainability of urban areas the following are recommended: (1) speed limits should be set to limit casualty risk, not according to driver choices,(2) roadways in developed areas should be designed with 10 ft lanes and on street parking and sidewalks, and (3) vehicle speeds in downtown and residential areas should be kept below 25 mi/h (preferably 20 mi/h), The paper also identifies gaps in knowledge about speed and sustainability.

Introduction

Sustainability is a hot topic recently, especially in the contexts of the environment, urban development and transportation. While preservation of the planet and its resources for use by future generations is an important element of sustainability, maintaining quality of life, or livability, for residents is also important to keep our cities sustainable. With the recent economic crises sweeping the globe, maintaining an ability to financially support societal values is also critical. The planning, design and operation of urban development and transportation are inextricably linked to sustainability. According to Woodcock [1], “Sustainability in urban design seeks to establish a sense of place by enhancing the public domain. This may be evidenced by an effective public transport network, safe streets, equity of access to retail and services as well as traditional commons such as parks.” Woodcock identifies one of the key metrics for evaluating a sustainable transportation design as a “reduced injury rate”. Similarly, the World Business Council for Sustainable Development, in its “Sustainable Mobility Project”, defines deaths and serious injuries by any travel mode as an indicator of sustainability [2]. Vehicle travel speeds are both directly and indirectly related to these metrics.

For example, the extent to which existing or proposed road network and urban development patterns contribute towards casualties in road crashes is an important element of the **equitable (or social) sustainability** of an area. Vehicle speed is an important indicator for crash casualties; therefore equitable sustainability can be compromised in neighborhoods exposed to vehicle speeds above acceptable levels.

Also, when residents do not feel safe walking or bicycling in an area due to the speeds on the roads being too high, that reduces the attractiveness of those modes, therefore reducing the public’s willingness to use them. This can make it more difficult to increase use of such modes in order to achieve **environmental sustainability** by reducing the generation of carbon and other harmful emissions. Higher vehicle speeds are associated with greater consumption of fuel and thus greater tailpipe emissions which also works against environmental sustainability.

As well, neo-traditional and traditional neighborhoods are proving to be highly desirable housing locations in the United States, largely on the basis of the walkability of the neighborhoods. Consequently, **economic sustainability** of newly developed and existing neighborhoods (especially property values) depends both on the traffic speeds being kept to levels low enough to keep people feeling safe walking and finding the neighborhoods livable and attractive, while still allowing adequate access to and from the area.

The objective of this paper is to explore how motor vehicle speeds are related to urban sustainability. Consequently, we specifically examine research into the following issues related to vehicle speeds:

1. How are vehicle speeds associated with road casualties?
2. How do vehicle speeds affect vulnerable road users (*e.g.*, pedestrians and bicyclists)?
3. How are vehicle speeds associated with harmful tailpipe emissions?
4. How are vehicle speeds associated with economic sustainability?
5. How can driver choice of speed be influenced by enforcement, environment (roadway and roadside design) and electronics?

The remaining sections of this paper address each of these questions, one by one; the final section summarizes the findings and presents recommendations defining how to achieve urban sustainability through vehicle speeds.

Vehicle Speeds and Road Casualties

Speed and Road Safety

There is a strong conceptual link between travel speed and road safety. Higher driving speeds provide drivers with less time to process information and react (illustrated in Figure 1 [3]). Furthermore, higher driving speeds usually result in higher collision speeds and an attendant increase in crash severity and crash fatality rates.

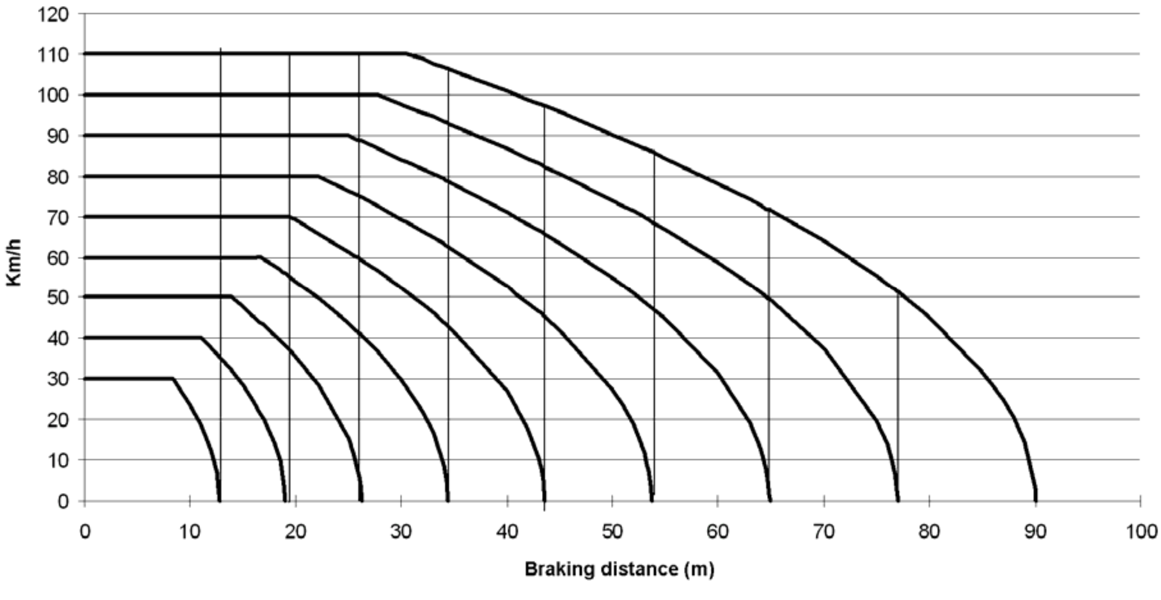

Figure 1Stopping distance in relation to driving speed, calculated with deceleration=0.8g and reaction time = 1 s (good conditions) [3]

Rosén *et al.* [4] summarized and analyzed much of the work up until 2009 into the connection between impact speed and injury severity of pedestrians hit by a car. Early studies have suffered from biases towards severe outcomes due to not taking sampling issues into account. The most reliable studies are presented in Figure 2. Note that above 75 km/h (about 46.6 mi/h) the pedestrian is more than 50 percent likely to be killed. The impact speed must be below 30 km/h (about 18.6 mi/h) to have negligible probability of being killed.

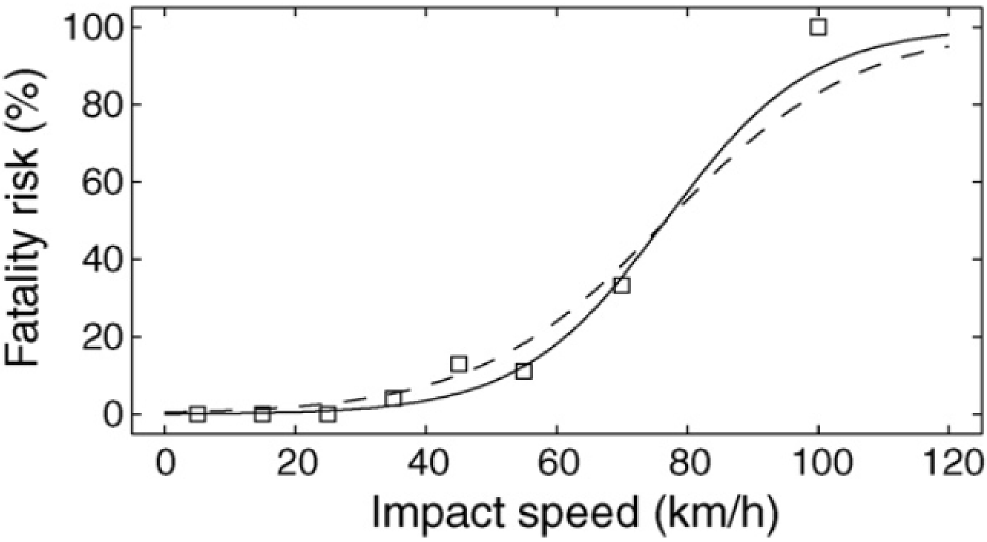

Figure 2 Fatality risk for pedestrians depending on impact speed of car [4]

Hauer[5] gives an overview of studies on speed and safety, noting several reasons why it is hard to identify this complex relationship. One reason is that crashes at higher speeds lead to higher severities and also have a higher reporting likelihood. They are thus more likely to be reported than those at lower speeds. Another reason is that for a study to focus on the known speeds of vehicles involved in crashes, the pre-crash speeds must be estimated, as it is impossible to observe them without a special study design. Consequently, the accuracy of the resulting analysis is dependent upon the quality of the pre-crash speed estimation. Finally, for crashes involving turning vehicles, the speeds at the time of impact will be lower due to the turning maneuver, and this would not be reflected in the distribution of speeds of general traffic on the road.

Another reason for the difficulty to identify the relationship between vehicle speeds and safety is the correlation between speed and just about every variable describing the road environment. In any cross-sectional comparison of crash rates between different road types, the high speed roads often have the lowest crash rates [6,7]. The roads with the highest speeds, freeways, have the lowest crash rates, not because of the high speeds but because of the safe design that cue the drivers to high speeds.

To explore this complicated relationship between vehicle speeds and safety, the next several sections each address different aspects of the relationship:

- Observed vehicle speeds and crash incidence
- Speed limit changes and crash incidence
- Observed speed variance and crash risk

Observed Vehicle Speeds and Crash Incidence

Stout and Souleyrette[8] conducted a case control study of automatic traffic recorder (ATR) speeds and crash incidence. They compared speeds collected for one hour at the time of a known crash with speeds in the same hour one week earlier. The mean of the vehicle speedswas significantly higher during the case hours (with a crash) relative to the control hours (without a crash) onboth freeways and two-lane roads. The variance was significantly different between case and control hours on freeways.

Davis *et al.*[9] performed a case control study of run-off road crashes considering pre-crash speeds of individual vehicles. The objective was to investigate the frequently reported U-shape relationship between speed and the probability of being in a crash. This study addressed several problems of previous efforts: (i) case speeds have usually included turning vehicles while control speeds were observed in free-flow; (ii) multi-vehicle collisions are more likely in congested traffic, and thus occur at lower speeds; (iii) most studies aggregate all collision types, whereas each collision type is more likely at a different speed than others. They addressed these issues using Bayesian methods to account for uncertainty in the observation of case speeds. They attempted to fit both linear and quadratic relationships between speed and crash incidence, and found that both fit equally well.The quadratic function monotonically increased over the entire range of observed speeds, as didthe linear function. Their conclusion was that if there is an increase in risk at lower speeds, it is for particular types of collisions and collision scenarios, such as freeway congestion, rather than cases where drivers choose lower speeds due to roadway and roadside design settings. They also note that higher speeds do not necessarily result in a crash, as many control speeds were higher than the crash speeds; the point is that the crashes occurred more frequently at higher observed vehicle speeds.

Speed Limit Changes and Crash Incidence

Nilsson [10] presents a model for the connection between a change in speed limit and crash occurrence as well as severity based on analysis of the safety outcomes resulting from speed limit changes in Sweden over a couple of decades. The findings are that the number of crashes expected on a specific traffic facility is proportional to the speed (limit, or running speed) to the power of an exponent and that the exponent differs between severities and is higher for more severe crashes. Nilsson proposed the exponent 2 for injury crashes, 3 for severe injury crashes and 4 for fatal crashes.

As an example, the equation referring to fatal accidents is:

$$\frac{Fatalaccidentsafter}{Fatalaccidentsbefore} = \left(\frac{Speedafter}{Speedbefore}\right)^4 \qquad (1)$$

Elvik*et al.*[11] revisited the Nilsson model and recommended best estimates for a modified version of the Power Model (Table 1)

Table 1 Speed and road accidents: an evaluation of the Power Model [11]

Accident or injury severity	**Exponent**	**Interval**
Fatalities	4.5	(4.1 – 4.9)
Seriously injured road user	3.0	(2.2 – 3.8)
Slightly injured road user	1.5	(1.0 – 2.0)
All injured road users (severity not stated)	2.7	(0.9 – 4.5)
Fatal accidents	3.6	(2.4 – 4.8)
Serious injury accidents	2.4	(1.1 – 3.7)
Slight injury accidents	1.2	(0.1 – 2.3)
All injury accidents (severity not stated)	2.0	(1.3 – 2.7)
Property-damage-only accidents	1.0	(0.2 – 1.8)

Friedman *et al.*[12] applied time series modeling to monthly fatalities in Israel for six years before and after the speed limit on interurban roads was raised from 90 to 100 km/h. In the six years before, fatalities declined steadily; after implementation, fatalities jumped in spite of countermeasures implemented, including road improvements and new laws requiring rear seat belt use. Fatalities increased on both interurban and urban roads, indicating a spillover effect: 12.7% of the deaths on interurban roads and 8.3% on urban roads (10.6% overall) were attributable to the change in speed limit.

Souleyrette *et al.*[13] studied the effect of raising the speed limit on rural interstates in Iowa from 65 mph to 70 mph. They found that the mean and 85th percentile speeds increased by two miles per hour, so that the proportion of drivers exceeding the speed limit by 10 mph or more was reduced from 20 to 8 percent. They found that the average rate of fatal crashes per year increased by 21.8 percent in the 2 ½ years following the change compared to the 14 ½ year period prior to the change. However, the average rate of serious crashes (fatal and major injury) per year actually decreased by 12.1 percent for the same comparison. It is possible that this change represents a shift in severity rather than an increase or decrease in crashes. This might be further illustrated by noting that the actual number of fatal crashes per year increased on average from 19.2 to 25.2, that is, 31.3 percent, while the actual number of serious crashes (fatal and major injury) increased from 78.8 to 90.8, or 15.2 percent.

Holló *et al.*[14] investigated the impacts of changing the speed limits in Hungary. The aim of this study was bifold; the authors studied the safety impacts inside (speed limit lowered from 60 to 50 km/h in 1993) as well as outside (speed limit raised by 10 km/h in all road categories in 2001) built-up areas. In the former case a control-group test was performed showing that the number of fatalities decreased by 18.2% in the following three-year period. In the latter case the author applied time series modeling and proved that after 2001 the number of fatalities increased significantly.

Observed Speed Variance and Crash Risk

It has been proposed that it is not vehicle speeds themselves that increase the probability of crash incidence, but rather the variation in speed[15, 16]. Lave [15] argues that it is not high speeds that increase the incidence of crashes but rather the high variation among the speeds of vehicles on a road, appealing to the notion that when all vehicles travel at about the same speed there is a lower risk of collisions occurring, irrespective of what that rate of speed is. Both Lave and Hauer [16] provide several examples demonstrating this relationship, with Hauer's being the most compelling. One of the extrapolations that have been made from this finding is the suggestion that a driver can reduce his crash risk by driving at the average speed of the other vehicles on a road—that is, reducing the difference between his speed and that of the other vehicles.

In contrast, Davis [17] argues that this association between higher speed variance and crash incidence is an "ecological fallacy", a phenomenon in which "a relationship observed between aggregated variables is necessarily attributed to the basic entities over which the aggregation was done". In other words, Davis argues that this relationship is an artifact of the aggregation of crash counts on individual roads. In particular, he points to the need to "distinguish between individual and aggregated measures of risk", and that "inferring a relationship between individual risk and speed dispersion from an observed relation between aggregated risk and speed dispersion is an ecological fallacy". Consequently, Davis does not dispute that aggregate crash risks are higher on roads with higher speed variance; he disputes that this observation can be translated into arguing that it is the higher speed variance that causes the increased crash risk.

Vehicle Speeds and Vulnerable Road Users

One important approach for increasing the environmental sustainability of urban areas is to reduce the demand for motorized vehicle travel through promotion of travel on foot and by bicycle. High vehicle speeds in a traffic environment deter people from walking. Alvén and Håkman [18] interviewed bus travelers and residents (potential bus travelers) about their mode choice; one of the main deterring factors making them choose modes of transport other than walking and biking was a perceived lack of safety due to high volumes and speeds on the roads near the bus stop. This section looks at research into how vehicle speeds may affect the safety of these modes and thus the attractiveness of them to travelers.

Davis *et al.*[19] studied the effect of vehicle volumes and speed on the severity of pedestrian / motor vehicle crashes and conflicts in the Twin Cities (Minnesota) area. They note that many jurisdictions in the US use the "85th percentile rule" for setting speed limits, that is, they set the speed limit at a level that is exceeded by no more than 15 percent of the drivers. The justification of this rule is to avoid enforcement problems and the notion, derived from micro-economics, that drivers will consistently choose their speeds to balance their desire to reach their destinations quickly with the risk of a collision. They further note, however, that this micro-economic model breaks down in the case of pedestrian / motor vehicle collisions. In this case, the pedestrian usually incurs nearly all of the personal costs of a collision, with the motorist's costs limited to minor property damage that is often covered by insurance, while the pedestrian experiences a physical injury resulting in personal pain and suffering and the loss of time and mobility. Consequently, in this "market" the rational motorist will choose a higher travel speed than the pedestrian would like. They note several studies confirming this; their own study observed speeds and traffic volumes on 25 residential streets and found that the probability of a pedestrian / motor vehicle crash occurring increased with the traffic volume but not with the traffic speeds, while the probability of a pedestrian / motor vehicle crash being severe increased with the traffic speeds but not with the volume. These findings certainly support reduction of vehicle speeds in locations where it is desired to increase the use of walking as a travel mode.

A FHWA report [20] describes development of intersection safety indices (ISI) for bicycles and pedestrians. The ISI is a rating between 1 and 6, with 1 being conditions that are safer for biking or walking, and 6 being conditions that are completely unsafe. These ratings were calibrated with a group of safety experts. In the ISI estimated for pedestrians, the 85^{th} percentile speed of traffic increased the ISI by 0.018 for each mi/h. In the ISI for bicyclists traveling through the intersection, a main street speed limit over 35 mi/h increased the ISI by 0.815 compared to roads with lower speed limits.

Vehicle Speeds and Tailpipe Emissions

One of the most obvious aspects of traffic related to sustainability is vehicle emissions. Vehicles emit chemicals that affect the health of those who dwell in the vicinity of the road, cause acidification and over-fertilization, as well as add to global warming. The amount of vehicle emissions depends on speed. Aggressive driving, for instance, can increase fuel consumption by 40% and emissions by up to eight times [21]. How the emissions vary with speed differs between the different types of emissions.

The emission levels of NOx depend mainly on the level of speed; the higher the speed the more NOx the vehicles will emit, but increased levels of acceleration will also increase the NOx emission rate [22,23].The emission levels of CO and CO_2 on the other hand do not depend as heavily on speed, though they can increase slightly with increased speed. For CO emissions, acceleration drastically increases the emission levels [24] compared to cruising at constant speed.

Smidfelt [25] studied street networks and features affecting emission levels for CO, HC and NOx. Humps and intersections are generally considered to increase emission levels, but the study found that if the system effects in a wider street network are studied, instead of just the effects close to the hump or intersection, then smoother speed profiles at lower speeds can generate lower emissions instead.

Jackson describes an experiment observing test runs with an instrumented passenger carto learn how to more accurately model the generation of ultrafine particulate emissions as a function of vehicle dynamics [26]. The vehicle was instrumented with an accelerometer, GPS receiver, OBDII scan tool and a particulate emissions collector. He found that high emission events of ultrafine particulate emissions occurred most frequently at locations where vehicles accelerate rapidly (greater than 3 mi/h/s) or must climb steep grades. This is a logical finding; it suggests that for environmental sustainability (with respect to air quality) it is more effective to reduce the need for vehicles to change speed rather than to force them to repeatedly reduce speeds and then accelerate. This suggests replacing traffic signals and stop controlled intersections with modern roundabouts and designing roads to carry vehicles at a constant speed rather than varying speeds.

Vehicle Speeds and Economic Sustainability

The direct effect of vehicle speeds on economic sustainability has been little researched, though it can be assumed there are both positive and negative effects. A positive effect would be the possibility to transport goods and people faster from one place to another, while a negative effect would be reduced attraction to live along the corridor of a high speed road due to noise and perceived unsafety. These effects have been studied indirectly through several studies looking at property values along roads and streets where the standard has been improved (and logically the speed increased).

Vadali and Sohn [27] studied the effect of the redesign of an expressway in Dallas, Texas on property values in its corridor. The study followed price changes during the project, but was reported before post-effects could be estimated. The conclusions were that properties closest to the expressway saw the largest effects, negative in the beginning of the project, but rebounding to positive towards the finalization of the project. Siethoff and Kockelman [28] studied similar effects of improvement to the US-183 corridor through Austin, Texas. The findings were similar to those of Vadali and Sohnwith negative impact during construction, but increased property values when finished, and the change in value decreasing with distance from the project. Carey and Semmens [29] studied the effect of freeway development on nearby land use and property values. The findings were ambiguous with increase in property values for some types of land use (multifamily housing and commercial property) and negative for some (single family housing), indicating that single family housing is more sensitive to disturbance. The most interesting result, though, was that the most negative impact on property values was not induced by the freeway per se, but by the increased traffic it induced on the roads in the area. A cross-sectional study of arterial corridors in Chicago Illinois [30] concluded that the more traffic there is on an arterial the lower the property values.

Iacono and Levinsson [31] studied home sales in Minnesota and the effect of freeway proximity on property values. They found that the proximity to the freeway itself reduced property values, but proximity to its access points increased property values. This further shows that disturbances from high speed road traffic, and the benefit of improved accessibility, work in opposite ways on economical values.

Achieving Sustainable Vehicle Speeds

Compliance with the posted speed limit is an important element of sustainability. As noted above, getting drivers to comply with the safe, sustainable speed on a street is a critical part of achieving sustainability from a transportation standpoint. There are three ways to achieve speed compliance: through enforcement, design of the roadway and roadside and through in-vehicle systems. This section discusses experience in each of these areas.

Speed Compliance through Enforcement

For this paper, we define “enforcement” to include law enforcement programs as well as programs adjusting how speed limits are chosen.

Rodier*et al.*[32] conducted a review of automatic speed enforcement programs in the US. Most of these programs were implemented on residential streets, with two exceptions, one program in the District of Columbia on a high speed arterial and another in Arizona on an urban freeway. The various programs resulted in a range of two to fifteen percent reduction in speeds and nine to fifty percent reduction in crashes. Very few of the programs turned a profit, and most required a subsidy. The authors note that public suspicion of a profit motive in the program turns opinion against the program. This suspicion can be averted by pledging to apply proceeds from the program to safety improvement funds. The biggest impediment is with implementation as such programs require enabling legislation at the State level and frequently face constitutionality challenges in the US. There are also issues with vehicle owner versus driver liability that must be addressed in the legislation.

Aarts*et al.*[33] describe "SACRED Speed", a program of SWOV (Dutch Institute for Road Safety Research) to set policy for determining speed limits. In this program, speed limits are set based on design, traffic mix and location of the facility, especially considering how pedestrians and bicyclists are accommodated. For example, without physical separation between motorized and non-motorized traffic, maximum speed of 30 km/h is indicated. Speeds of 80 km/h or more are permitted only with separation of driving directions and a forgiving roadside. This program identifies "accelerators" and "decelerators", factors which increase or decrease the expected reasonable or credible speed as perceived by drivers. It also discusses the role of enforcement, seeking to not require the police to enforce limits that the public deems to be inappropriately low, reducing respect for the law enforcement.

Similar guidelines for setting speed limits according to traffic mix have also been developed in Sweden in the late nineties, following the adoption of the Vision Zero [34]. Guidelines for urban areas were developed stating: The speed limit should not exceed 30 km/h on streets and at crossing points where vulnerable road users are found. The speed limit should not exceed 50 km/h where angle collisions between motor vehicles are possible. And where head-to-head collisions are possible the speed limit should not exceed 70 km/h. These limits were set based on the collision forces that the combination of the human body and the protection of the vehicle can sustain without considerable risk of fatal outcome [35]. Following the introduction of new speed limits in 2008 there were further guidelines developed detailing how the speed limit should be set according to the design of the road, for instance separation of vulnerable road users, presence of median barriers, *etc*.

Hydén *et al.*[36] studied the change in speed during a test with new speed limits in twelve Swedish cities. The speed limits were lowered on most of the streets, from 70 to 60 km/h, and from 50 to either 40 or 30 km/h, but for some streets the speed limits were increased from 50 to 60 km/h or from 30 to 40 km/h. On average a decrease of the speed limit resulted in a decrease of the actual speeds by 2-3 km/h, and an increase of the speed limit resulted in an increase of the actual speeds by 0-1 km/h. The changes of actual speeds were found to depend on the speed before the change. In most of the cases the speed limit was changed to better agree with the actual speeds, resulting in smaller deviation in speeds between vehicles.

Speed Compliance through Roadway and Roadside Design

The second approach to achieving desired vehicle speeds is by roadway and roadside design. This area has seen much work since the early nineties starting in The Netherlands under the name 'Self-explaining Roads' [37]. The idea of self-explaining roads is that the road design should give the driver the right expectations and elicit a correct behavior. An ideal self-explaining road should, in theory, not even need a speed limit since it should make it evident to the driver what the correct speed would be. In fact, according to an FHWA report, simply reducing the posted speed limit on a roadway, even by as much as 15 mph, had no impact on mean travel speeds and did not reduce accident rates [38].Therefore, achieving sustainable, safe speeds on urban and suburban roads depends upon creating the right roadway and roadside environment to guide drivers to choose a speed that is safe for them and for other road users.

Hansen *et al.*[39] explored the relationship between roadway and roadside characteristics and observed vehicle free flow speeds. Again, they observed free flow speeds using handheld radar guns at 272 locations on two lane roads in Connecticut. Roadway characteristics that were also collected included lane and shoulder width, presence of curbs and edge delineation types. Roadside characteristics included: presence of on-street parking, presence of sidewalks, size of the building setback, driveway density and land use types. Analysis of variance was employed to identify significant variables in predicting mean speeds. They observed higher speeds on roads having wide shoulders, large building setbacks, no sidewalks or on-street parking and residential locations. They found the difference in mean speeds to be as high as 10 mph between roads with different combinations of roadway and roadside design features. Based on their findings, they recommend that roads in settled areas be designed to have shoulders of no more than two feet in width, and including sidewalks and on-street parking to encourage drivers to travel at slower speeds that will promote greater safety for non-drivers.

Gorrill [40] prepared a synthesis of traffic calming experience on rural roads. They summarized findings from various studies regarding physical and operational measures to reduce speeds on rural roads, both through roads and minor roads. They found that the most effective treatments were speed tables, though they also received the most complaints from residents. Otherwise, center islands that provided longitudinal narrowing worked the best.

Weller *et al.*[41] conducted a psychological laboratory study using photographs of rural roads to categorize roads by the speeds that drivers chose to drive on them. They found that drivers' speeds tend to be higher when either comfort or monotony is considered to be high.

Speed Compliance through In-vehicle Systems

Cunto*et al.*[42] conducted a study of truck speed limiters, with simulation using VISSIM. Safety was represented by a Crash Potential Index (CPI). They simulated scenarios with trucks having speed limiters at 105 km/h. They found that the introduction of speed limiters would improve safety in uncongested conditions, especially on simple freeway segments. The safety gains are reduced as traffic volumes increase, and actually reverse in congested conditions in the vicinity of on and off ramps. The issue in those situations is increased vehicle interactions and the likelihood of being unable to avoid a collision.

Extensive experiments with speed limiters in cars have been carried out in Sweden during 1999-2002within the project named ISA (Intelligent Speed Adaptation). The experiments were conducted in four different cities, and with different systems with different levels of feedback/guidance with regards to: 1) in-vehicle information about the speed limit, 2) warnings about speeding through sound or light and 3) actual limitations of the possible driving speed [43].

The main findings were (quoted directly from the source):

- Better road safety without increasing travel time
- If everyone had ISA, there could be 20% fewer road injuries in urban areas
- High acceptance of ISA, and after the trial most test drivers were of the opinion that ISA should be compulsory in urban areas
- ISA vehicles were found to have a positive influence on surrounding traffic
- Minor differences between the systems, with an average speed reduction of 3-4 km/h on stretches between intersections
- The systems must be improved to become more attractive.

Results from the ISA experiments with actual limitation of the speed were further studied in a doctoral dissertation by Hjälmdahl [44]. The system used an Active Accelerator Pedal (AAP) that gave a much increased back-pressure when the speed limit was reached. The conclusions were that drivers using the system were both driving with a reduced mean speed as well as reduced speed variance. The author estimated an injury reduction of up to 25 percent if all vehicles were equipped with the system.

Conclusions

This paper has demonstrated that high vehicle speeds can exasperate initiatives to improve urban sustainability in several ways:

1. High vehicle speeds increase the likelihood of pedestrians being killed when struck by a motor vehicle, and the general severity level of any crash, reducing *equitable sustainability*;
2. High vehicle speeds increase the generation of NO_x emissions, reducing *environmental sustainability*; and
3. High vehicle speeds have mixed effects for economic sustainability; they reduce sustainability by negatively affecting the attractiveness and marketability of residential neighborhoods in close proximity to high speed roads, but access to high speed roads also increases economic sustainability in urban areas as it is critical for movement of people and goods.

Furthermore, the paper has identified certain critical speed thresholds that are useful for defining what a sustainable speed for various urban environments is. For example:

1. Speeds below 30 km/h (18.6 mi/h) result in negligible risk of pedestrian fatalities;
2. At speeds above 75 km/h (46.5 mi/h) a pedestrian is more than 50 percent likely to be killed in a collision with a motor vehicle; and
3. Reducing vehicle speed changes has greater benefits for environmental sustainability.

Finally, the paper has shown that, apart from traditional police enforcement, it is possible to influence driver speeds to sustainable levels:

1. Automated enforcement can reduce speeds up to 15 percent and crashes up to 50 percent;
2. Setting speed limits according to rational outcomes rather than by observed 85^{th} percentile driver speeds can achieve speed limits set at levels appropriate to the land context and reduce crash casualties;
3. Drivers consistently take cues from roadway and roadside design elements about the appropriate speed to choose; and
4. Drivers will accept technology to help them control their speeds at safer levels.

As a result of these findings, we recommend that urban road authorities consider managing vehicle speeds in their jurisdictions as a critical element of their plans to achieve sustainability. In particular, we recommend the following:

1. Consider guidelines such as the Dutch SACRED speed or the Swedish Vision Zero for setting speed limits in urban areas.
2. Consider limiting lane and shoulder widths and including sidewalks and on-street parking in settled areas, especially in residential zones.
3. Speeds in areas with human development, especially pedestrian activity, should be kept lower than 25 mi/h, preferably 20 mi/h, to eliminate pedestrian fatalities.
4. Roads should only be designed with speeds greater than 30 mi/h outside urbanized areas or in urbanized areas where pedestrian and bicycle facilities are physically separated from motor vehicles.

In urbanized areas it is important to distinguish between streets providing direct access to human activity and land development and those that do not provide direct access to human activity and land development. The former type of street should focus on access and have lower speeds. The latter type of street could have higher speeds to serve the mobility function, provided pedestrians are adequately separated from motor vehicles. There should be a balanced network of both types of streets in the city, with a limited number of the higher speed streets. At the same time, our review of existing research has revealed the following shortcomings in the extant knowledge about speed and sustainability:

1. It is extremely difficult to isolate the association between speed and crash incidence. Some researchers have made great strides using causal analysis (*e.g.*, Davis [9]) and other microscopic approaches to account for pre-crash speeds of vehicles that were actually in collisions as compared to the running speeds of vehicles not in collisions. Unfortunately, none of the existing research is able to cite specific speed thresholds associated with reduced crash rates.
2. Vehicle emissions are related more to acceleration than to speeds. Consequently, research is needed into how various speed, road design and land development scenarios impact vehicle accelerations.

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