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The influence of road design speed, posted speed limits and lane widths on speed selection—a literature synthesis

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Abstract

Drivers select the speed at which they travel as a function of a variety of driving clues and risk assessment, directly affecting the operating speed of that road. Resulting speed distributions are routinely used to justify posted speeds. Operating speeds are fundamental to the development of any roadway corridor and are used to determine appropriate roadway design elements. Roadway corridors are generally developed to maintain the tenents of cross section consistency, operating speed consistency, and driver work-load consistency.

These tenents are interrelated within a road corridor and must be designed to ensure appropriate speed choices are made. Some empirical evidence suggests that narrower roads, and narrower lanes on roads, lead to slower travel speeds. In contrast, the literature reveals that the effects of narrower cross-sections to lower traffic speeds, and associated crash frequencies, have been inconsistent. Some researchers have concluded that reducing lane widths had no impact on speed selection. Moreover, a lack of geometric design consistency and the associated disparity with drivers' expectations has led to increased crash rates when differences between design and posted speeds exist. Whilst it is important to be aware of corridor characteristics such as the road grade, cross-section and surface conditions, there has been insufficient research to accurately understand their impacts on speed choice (distributions) and associated design and posted speeds. This paper addresses the gap in the literature and provides a current and comprehensive literature synthesis on this important subject, identifying research gaps and critical research needs moving forward.

1. Introduction

Road crashes are a leading cause of death and injury both in Australia and worldwide, with significant economic and social costs [1]-[4], especially among young people [5]. In 2003, road crashes were responsible for over 1600 Australian deaths and estimated to cost $17 billion equating to approximately 2.3% of Australia's Gross Domestic Product [3]. Seven years later, in 2010 road crashes accounted for over 1300 lives [4]. The *Road Safety Strategy 2011-2020* increases this to about 1400 Australians and 32500 hospitalisations and equates to a society cost of approximately $27 billion [6]. Most injuries and crashes are the unintended consequences of individual actions in a risky environment; they are not due to fate or to problem behaviour [7] and are therefore subject to countermeasures.

Road safety is important yet some researchers like Aggeloussi, et al., (5) question how much people are disposed to changing their behaviour? Driver behaviour is complex and involves many differencing factors often at odds with each other and therefore complicated to predict. As an example, some drivers see trip time as more important than their safety, as they cannot quantify safety as easily [7]. Speed and excessive speed remains a main contributing factor to road crashes [12]-[14] and is an important factor in road safety. Not only does it affect the severity of a crash, but is also related to the risk of being involved in a crash [9]-[13]. Without exception, a vehicle that moves faster than other vehicles around it has a higher potential crash rate [9]. Excessive speed in Australia was assigned as a major factor in fatal crashes more frequently in the 2000s than in the 1990s where it averaged 28% of crashes. This figure increased to 33% by 2006 [15].

Once a crash occurs, the relationship between speed and the outcome of a crash is directly related to the kinetic energy that is released during the collision and hence quite straight-forward; whereas the relationship between speed and the risk of a crash is much more complex [8],[10]. Attempts have been made to model multiple causal influences on driver behaviour that impact on speed choice [16] and is explored later.

Although countermeasures for some high risk behaviours such as random breath testing and speed cameras have reduced deaths and injuries over the past two decades, some argue that these reductions appear to have essentially plateau since 2003 [4]. Mannering, (9) believes for whatever reason, respect for speed limits have deteriorated over this time. If accurate, a general disrespect for speed limits can potentially lead to widespread behavioural problems [8]. Notwithstanding any debate about whether crashes have plateau, with the continued influence and impact of speed, continued exploration into the connection between speed (choice) and road crashes is warranted.

Drivers select the speed at which they travel, directly affecting the operating speed of that road. In reverse, the road environment affects the choice of speed by drivers. The operating speed is fundamental to the development of any roadway facility through geometric design elements and used to determine an appropriate design speed [21]. It is a complex and often circulatory relationship between the design speed and operating speed. At a geometric detailed level, elements such as: lane width; junction density; and traffic flow interact with the speed–crash rate relationship [8]. With operating speeds fundamental to the development of any roadway corridor, they are used to determine a design speed which is used in the selection of appropriate roadway design elements. Whilst it is important to be aware of corridor characteristics such as the road grade, cross-section and surface conditions, there has been insufficient research to accurately understand their impacts on speed choice (distributions) and associated design and posted speeds. This paper forms part of a literature synthesis to help understand the relationship between operating speeds and speed choice. Then by extension this will help refine the road design process and provide an opportunity to improve the determination of speed limit settings.

2. Speed choice and design elements

Safety is a primary consideration in the establishment of standards for geometric design elements and in Australia a Safe System Framework approach to road safety has been adopted which assumes that motorists will make errors while using the road network [22]. This approach aims to provide a road system that protects responsible road users from death and serious injury, recognising that road users are fallible and will continue to make mistakes, but that they should not penalised with death or serious injury when they do make mistakes [22]. Therefore, the road system and geometric design elements need to be designed so that when errors do occur, road users of all types avoid death or serious injury as a result of those errors. However, geometric design guides generally do not provide quantitative information on the relationships between crash risk and the standard which should be selected for that specific design element [22].

As a result, typically decisions regarding the adoption of ‘above minimum’ standards or a standard less than the recommended value usually as a result of a constrained situation, have to be made with only a limited appreciation of the safety implications [22].

A method to address this decision making in Australia is through context sensitive design (CSD) and considers characteristics of a complete transport system such as the road grade, cross-section and surface conditions which affect the operating speed of the road [24],[50]. This design approach aims to achieve an appropriate balance between safety, mobility, community and environment needs when developing geometric design element solutions [24],[50]. The design process essentially becomes a question of balancing cost against risk, rather than simply attempting to decide which solution is "correct" verses "incorrect".

Furthermore, since it is not possible to create a completely safe road whilst there is human involvement, each design will be "more safe" or "less safe" than some other alternative however, each outcome should be ultimately moving towards a goal of zero fatalities. The appropriate balance then depends on the combination of design elements used to produce the road corridor. Finding the appropriable balance between cost and risk relies on experience and judgment assisted by objective measurement and research. Despite a desire to move towards zero fatalities, is it being achieved? The question arises as to whether this appropriate is diametrically opposite to the Safe System approach. What becomes the resultant design outcome in the jurisdictions where both systems being adopted? Undoubtedly compromises would result where there is conflicting outcome required from the philosophies.

Different road functions exist within the each road system reflecting the type of service provided by the road. In addition, there can be significant topography variations from area to area. This variation needs to be accommodated as part of good road design any project design stage. Different cross-sections are typically introduced when the function or the road topography changes. Hedlund,(16) found there was higher consistency in speed choice where segments of the road were homogenous and there was consistency in relation to speed limit and varied as a function of roads and direction of travel.

McLean,(34) states that different cross sections treatments can have a substantial effect on crash rates. Road geometry and other characteristics will influence drivers' expectations of the appropriate speed for a road [16],[29] and when an inconsistency exists that violates driver's expectation, the driver may adopt an inappropriate speed or inappropriate manoeuvrer, potentially leading to road crashes [23]. Like Hedlund,(8), Fildes & Jarvis,(27) emphasise the importance of changes or inconsistencies in road design, which are a mixture of sensory and cognitive aspects. In contrast, when design consistency is ensured, all abrupt changes in geometric features are eliminated, it prevents critical driving manoeuvres and minimizes crashes [23].

Driver errors and crashes are more likely to occur when there is some disparity between what drivers may believe to be a 'safe' speed and the actual speed at which a feature can be negotiated safely [24]. For these reasons, agencies like the Transportation Association of Canada [24] and the Queensland Department of Transport and Main Roads clearly articulate that there should be consistency of design for each type of function in each terrain type regardless of location [24]. Of particular interest, Sayed,(23) stated that little work had been carried out to quantify the safety benefits of geometric design consistency. Similarly, Shinar's,(51) review revealed only a few studies directly investigated the effect of roadway design on driver behaviour through controlled manipulations [50].

Road design consistency becomes critical to the reduction in driver decision making uncertainty and leads to the concept of a "self-explaining road" [27],[32],[50]. That is, a road whose geometric elements, layout and features inform the driver what type of road it is and therefore what can be expected. The concept of self-explaining roads then involves designing a road system in which the driver's expectations created by the geometric features of the road environment are implicitly in line with the safe, appropriate behaviour for the road [27],[32],[50]. Ideally, the outcome for a self-explaining road design is to produce a corridor properly designed in terms of road and lane width, junction density, traffic flow, horizontal and vertical curvature meeting drivers expectations to reduce potential errors [9],[24],[27],[32],[50]. Additional aspects of the actual road infrastructure that influence driver expectation and by extension speed choice include: road shoulder width; number of lanes; radius of road curvature; length of curves; delineator type and number; delineator spacing; condition of delineators; pavement markings; road edge guide posts; signing conventions; intersecting driveways; intersection treatments; traffic flow; traffic conditions; clear zones arrangements; parked cars; roadside environment; and the roadway grade [9],[23],[24].

In this style of self-explaining road environment, drivers are able to confidently operate safely at their desired speed along the entire alignment [27],[48]. On that basis, it should be possible to manipulate driver speed choice through changes in road design, rather than merely relying on signage or other cognitive aspects. This then leads to the issue of driver cognitive workload. The roadway geometry, traffic conditions, and roadside environment are the primary inputs to the driving task that determine the workload requirement of the driver [23]. This will be touched on later. However, choice of speed may be affected by factors other than road infrastructure, such as age, risk of apprehension and attitudes and moreover interact with each other [16].

With respect to the concept of consistency, the Department of Transport and Main Roads (2005) form road corridors with following basic design tenents [23],[24]: cross section consistency; operating speed consistency; and driver workload consistency. The following sections will discuss each of these tenents in more detail.

3. Road corridors

The road is but one element of a complete transport system, which operates in the natural and built environment to meet a range of user expectations and the broader community and as such, cannot be designed in isolation, but rather, it must be sensitive to the context in which the road will operate [50]. A method to achieve this in Australia is through CSD and should consider characteristics of a complete transport system such as the road grade, cross-section and surface conditions which affects the operating speed of the road [24],[50]. Road network design is one of the most significant factors that affect driving behaviour and perceived safety [50].

As mentioned previously, CSD is a design approach that aims to achieve an appropriate balance between safety, mobility, community and environment needs when developing geometric design element solutions [21],[24],[50]. Again, alternatively a Safe System Framework approach in part manages speed taking into account the risks on different parts of the road system [21]. Whether this approach is at odds to CSD needs to be explored.

The roadway geometry, traffic conditions, and roadside environment are the primary inputs to the driving task that determine the workload required of the driver. Cross section, operating speed and driver workload consistency become a fundamental issue in the development of actual road corridor infrastructure [23],[24]. Aspects of actual road infrastructure that influence speed choice [9],[23],[24],[44],[50] include: lane width, road width, road shoulder width; number of lanes; horizontal and vertical geometry; curvature; grade; signage; delineators; pavement markings; intersecting roads, driveways and treatments; traffic flow and conditions; clear zones arrangements; parked vehicles; and roadside environment. The challenge is to develop a road design solution that takes account of the competing alternatives and the trade-offs that might be needed due to limited corridor space and should consider the following factors: mobility; reliability; environmental impacts; safety; loss of design consistency; reduction in the life of the infrastructure; capital costs; whole of life costs; and aesthetics.

There are many aspects to be considered in the planning and design of road projects with road design speeds being selected and roadway corridors designed in accordance with the design domain philosophy which are then reflected in the posted speed limit [21],[24],[50]. Cross-section elements such as the width and the number of lanes have the strongest influence on driver's perceptions of safety and travel speeds and should be similar as they impact on operating speed [33]. A narrow, confined cross-section is likely to result in a slower speed of operation than one with similar geometric characteristics but a wide, open cross section. Again, Haglund & Aberg,(16) found there was higher consistency in speed choice where segments of the road were homogenous with consistent speed limits which varied as a function of roads and direction of travel. Generally, drivers make fewer errors at geometric features that conform with their expectations such as those expected in a self-explaining road [27],[32],[50]. On that basis it is important to provide a consistency of design for each type of function in each terrain type regardless of location [29]. Shinar's,(51) review revealed only a few studies directly investigated the effect of roadway design on driver behaviour through controlled manipulations. With the little research carried out to quantify the safety benefits of geometric design consistency [21],[23],[50].

This lack of research and understanding is certainly of interest. Perhaps in the absence of this research, practitioners and road designers are adopting more anecdotal practices. Given the relationship between speed and safety it is worth further exploring speed choice and the link between geometric designs, whether consistency or lack of consistency is of interest.

4. Lane and shoulder width

Lane and shoulder width plays a role in driver speed choice as empirical evidence generally suggests that narrower roads, and narrower lanes on roads, lead to slower travel speeds with more of an influence from other traffic (meeting traffic or overtaking traffic) and of obstacles along the side of the road [23],[24],[27],[50].

Reducing lane width leads to lower speeds and crash frequency [38],[39] but the effects depend on specific lane widths and road types [21],[27],[40]. As an example, decreasing lane width beyond a certain point (close to the width of the car) makes driving practically impossible [27] so simply continued reduction in width is not possible. That said, Fildes et al.,(37) argued that narrowed walled settings: making the driving environment appear less safe for drivers, could help reduce travel speeds [33]. With smaller lanes, more effort must be put into lane keeping and steering behaviour and as a consequence, driving speed usually decreases with lane width [27]. Whilst this seems to be the case, 'usually' does imply a level of doubt on the outcome. As mentioned, reducing lane widths can bring opposing vehicles travelling in opposite directions closer. In doing so, the reduction in crash risk by reducing lane width, hence speed, could very well be negated by the increased risk of head on crashes. Godley,(25) argues the only possible way to reduce speed and the chance of crashes is through narrower “perceptual” lane widths. The change in width is only perceptual and can be achieved where the width of the sealed road remains constant whilst the delineated driving lanes within that area are narrowed with the introduction of say, a wider median [25]. In this example, the reduction in lanes could be undertaken if the lanes themselves were separated by a wider centreline.

Shinar,(51) found no main effects for the shoulder width factor and Auberlet et.al.,(49) concluded that reducing the lane width had no impact on speeds. Lum in Goodley,(25) found that narrower road widths and narrower shoulder widths both led to slower free speeds however there were no speed differences between physically wide lanes and perceptually narrow lanes. They surmised that this may have been a result of the low measured speeds (60km/h) and speculated that if the lanes were narrower, and/or traffic speeds were faster, different results may have been found. This research is quite dated now. Perhaps over time generational change may influence the outcomes. Similarly dated work by the OECD,(29) concluded that widening the total sealed road leads to faster speeds, for drivers who were both familiar and unfamiliar with the roads. The effect of road width on driver speed choice seems to depend on the amount of pavement the driver perceives as usable. This is affected by the lane width, number of lanes, sealing and/or widening the shoulders, shoulder width, presence of parked cars on the edge, and presence of vertical elements on the roadside [27]. Leong in Goodley,(25) however demonstrated that narrowing perceptual lane widths will not necessarily result in slower driving speeds but could be accounted for by the static width of a shoulder.

Road width impacts appear to have inconsistent effects: whilst there is research that show reducing lane width leads to lower speeds and crash frequency [38],[39] others such Summala in Shinar, (51) believe narrower roads could be perceived as less tolerant. In this way they are more dangerous, leading drivers to use speed control as a mean to avoid danger or risky situations and possibly increasing the risk of head-on and run-off-road crashes [27],[40]. Road width increase (or are perceived as wider), drivers increase speed, and thus crash risk increases [25],[27],[36],[40] leads to the question as to what is an appropriate width? The lack of recent research is worth noting.

Nevertheless, extra pavement width, such as extra available space next to the driving lanes does not always have to affect driving speed [27]. Narrow shoulders can create a dangerous situation where the driver will not have recovery area in case of lane deviation and they therefore increase the likelihood of off-road [50]. Shinar,(51) found that the shoulder width had a significant effect on actual speed, on lane position, and on perceived safe driving speed, but only when a guardrail was present [50]. However, Noland,(47) did find that increases in outside shoulder width appear to be associated with reduced crashes, but show a positive but statistically nonsignificant association with increased fatalities. Shinar, (51) found no main effects for the shoulder width factor.

Increases in lane and shoulder width have sometimes been recommended as a means of making curves more forgiving which can also have the effect of increasing drivers' speeds therefore potentially increase crash risk[41]. However, Noland, (47) found no statistical association with changes in safety is found for median widths, inside shoulder widths, and horizontal and vertical curvature. The research doesn't seem to be conclusive and raises questions about experimental design and evaluation methods.

Two-lane rural roads have been constructed to a wide range of lane and shoulder width standards over the years and been the focus of many studies with considerable research into the effects of their standards on safety performance [18],[22]. As highlighted before, Austroads,(22) identified that the majority of these studies are relatively old and typically have a focus on rural roads however have been used to develop and calibrate crash prediction models.

To continue contra views, Noland,(47) rejects the hypothesis that improved road infrastructure geometric design is beneficial for safety and suggest that some changes in infrastructure have actually led to increased fatalities. Furthermore, Noland,(47) found that increases in the number of lanes appears to be associated with both increased traffic-related crashes and fatalities whilst increases in outside shoulder width appear to be associated with a decrease in crashes. The increase with number of lanes could easily be associated with increases in exposure. Additional lanes will allow for a growth in traffic volumes. With more vehicles there is higher exposure and this could be associated with the findings of increased crashes and fatalities. It is important to understand this relationship and the impact on reducing crashes rates. Simple reducing the vehicle speed will impact on road safety however; the full impact on speed reductions to reduce either crashes rates or frequencies is outside the scope of this literature synthesis.

Intuitively, it would be presumed that new and improved road designs have a positive impact on road safety and perhaps ensured speeds were more comparable to design speeds. This presumption may not always be correct, and more work is needed to understand these complex relationships. There certainly are conflicting results found in the research reviewed with limited focus on urban roads. Noland (2003) actually has challenged whether new and improved road designs actually produced fatality reductions in the US and found that increased seat-belt usage, demographic change, and improvements in medical care seem to be more associated with fatality reductions over time than various improvements to the road network (which included lane widths, road classes, number of lanes).

A better understanding and quantification of the safety implications of geometric improvements and countermeasures is warranted, especially with regard to the impact of any change to the cross-section [33].

As previously mentioned, there is little information available on the issue of lane width research for urban areas [18],[22],[25],[27]. This could be a result of the fact it is very difficult to measure the effect of pavement width in itself, or other elements of the roadway corridor, independently of other road design factors and have been used to explain inconsistencies in associated studies [27],[29]. In addition to these logistical factors there are ethical issues with trialling different geometric infrastructure elements on the general public. Driving simulators provide a useful tool to overcome these issues and run simulations with different road designs treatments, varying some elements whilst keeping other road design factors constant. As some road design treatments may result in an unsafe road, using a simulator removes the risk of actual injuries or deaths from occurring. Simulators could be useful to explore lane width issues for urban areas. One of the key issues with the use of simulators is understanding, if any, the differences between behaviours of drivers in a simulation and those in a real environment and ensuring that they reflect each other [29],[34].

There is merit in undertaking further research into the impact of lane and shoulder widths with respect to drivers speed. Whilst there is little information available on this issue for urban areas McLean,(34) has drawn the following conclusions on safety performance of cross-section elements and treatments one of the few studies looking at urban arterial roads [22]:

1. The findings from studies on the effects of urban surface arterial width standards and cross-section treatments on crash frequencies are more variable than those pertaining to rural arterial roads given the complexity of urban arterial operations as related to the mix of through traffic, local circulation, and property access functions they perform;
2. Within the range of practical lane widths (say 2.75 to 3.75 m), lane width itself has only a small effect on crash rates for urban arterial roads;
3. Only Heimbach et. al.,(35) found a statistically significant effect for lane width reductions that reduced crash rates by 2 to 2.5% per 0.25 m increment in lane width;
4. Different cross-section treatments can have a substantial effect on crash rates;
5. Density of access to the arterial from un-signalised side streets and driveways has a greater effect on crash rates than the cross-section treatment; and
6. Commercial versus residential effect on adjoining land-use is of a similar order to that of access density.

The literature [22],[24],[25],[27],[29],[49],[50] suggests that the results found relatively that the impact of a lane width changes on road safety are inconsistent, which does suggest there is scope to apply some level of further exploration on the issue.

5. Driver workload

Roadway geometry, traffic conditions, and roadside environment are the primary inputs to the driving task that determine the workload requirement of the driver [7][18][19],[24][25]. An important workload factor contributing to the perception of appropriate speed is the 'information density' of the road environment [2]. This density of information can have significant effects of driver speed choice, by influencing driver's perceptions of their own speed and their perceptions of the appropriate speed for a road [27].

Perceptual countermeasures, which aim to implicitly affect drivers' perceptions of how fast they are travelling, are a well-established research area. Engineering treatments to force drivers to slow down are common however there is less information of how road environment factors affect drivers' perceptions of the appropriate travel speed for a particular road, without physically slowing traffic [27].

Workload consistency is a fundamental issue in the development of actual road corridor infrastructure [23],[24]. Sender et.al., in Martins et. al.,(28) showed that drivers need to obtain information from the road ahead at such a rate so as to reduce uncertainty about the upcoming manoeuvres required, but not so fast as to allow insufficient time to process the information. When an inconsistency exists that violates driver's expectation, the driver may adopt an inappropriate speed or inappropriate manoeuvre, potentially leading to increased crash risk [23]. Importantly, this requires that the information context of the environment be clear to drivers so that they can modify their speed choice behaviour appropriately [27]. In contrast, Lewis-Evans,(30) found that drivers who are under cognitive load are not as good at maintaining speeds, lower than they would typically drive, as they are at maintaining speeds higher than normal at least for short periods.

Driver workload has a marked effect on performance at both end of the spectrum, both too much and too little [23],[24]. If the demand is too low, the driver's attention will be too low with probable loss of vigilance and they may even fall asleep at the wheel. At the other end of the spectrum, if the arousal level is too high (such as stress, information overload, and emotional situations) the driver may compensate by ignoring some relevant information leading to unsafe vehicle operation [23],[24].

6. Design, posted and operating speeds

Ideally the design of a roadway creates an environment whereby drivers select appropriate and safe speeds for the road corridor. Roadway geometry, including horizontal and vertical curves (radii), lane widths, shoulder widths, and sight distances all play roles in the "design speed" of a road which is vehicle speed which the road is designed to accommodate. Designers use the design speed in design process such as the selection of standards.

In Queensland, the Department of Transport and Main Roads,(43) often adopt the design speed as the 95th percentile speed of free-flowing traffic "expected to occur as a function of the adopted" design standard of a road. The design speed is not to be confused with the operating speed which is discussed later. Garber and Gadiraju,(31) found that the difference between design speed and (posted) speed limit plays a role crash rates. Whilst the average speed mainly corresponded to the design speed, the crash rate and speed variance was lowest when the speed limit was approximately 8-16 km/h lower than the design speed [9]. Haglund & Aberg,(16) found that with their speed measurements the mean speeds were above the posted speed limits with no consistency in behaviour between urban and rural sites or between the different urban sites. Perhaps this can be attributed to the fact that sometimes a speed limit is changed because of a change in road function or an upcoming hazard and the change may not always be obvious to the driver.

Richards & Dudek,(26) refer to changed speed limit with just a static sign as passive speed control and generally only sufficient at sites where the hazards are obvious. With obvious reasons for speed limits, drivers accept the speed limitation [27] and this outcome is in the style of a self-explaining road [24],[29]. Just relying on signage is not enough. For example, Cameron,(20) found that in urban areas, 26% of drivers were unaware of the speed limit and that these drivers were observed to be driving faster than others [11],[20]. Without the self-explaining road the effect of the speed limit signage is reduced. Difference in speed limit is thus motivated by differences in road standard [16]. Changing the posted speed without changing other factors of the roadway corridor that influence speed choice can lead to an increase of crash risk [24],[29].

In recent decades, it has become more common for speed limits to be set for political reasons rather than for safety reasons resulting in the community increasingly questioning the rationality of speed limits [9]. A key motivating factor in drivers' tendency to exceed the speed limit is that they believe that the excess speed does not threaten safety [9]. A prime example is where the speed limit has been reduced following a series of crashes. With the cost of changes to infrastructure being expensive and cost prohibitive, it is often easier to simply lower a speed limit. This can increase the difference between a new posted speed and the design speed. What effect does this have on driver behaviour and speed choice? Given little work had been carried out to quantify the safety benefits of geometric design consistency (in urban areas) and only a few studies directly investigated the effect of roadway design on driver behaviour through controlled manipulations [21][23][50] further investigation is warranted.

Speed limits are typically determined with the intention that credible limits are established to maintain a balance between a road user's reasonable perception of the speed environment and an acceptable level of environmental amenity for all road users and abutting land users [16],[43]. There is a significant assumption that drivers knowledge and experience are appropriate to drive safely.

To achieve this balance, similar to design speed, a number of safety factors and criteria are considered when determining an appropriate speed limit and done within the context of the Safe System [44]. These factors are not simply a standard or the appearance of a road [43] and include: environment in which the road is located; pavement, shoulder and lane width; horizontal and vertical road alignment; traffic volume, activity and prevailing speeds; frequency of intersections and property access [43]. There are recurring factors that have influence speed limits as well as design and posted speeds. Notwithstanding, one of the most important consideration in review of a speed limit should be the determination of the crash rate of the road [44]. Despite these considerations, road authorities often change speed limits after the road opens to traffic. Changes to speed limits occur for a variety of reasons from political (community) pressure, new works undertaken within the road section or changes to adjoining land use. The result being that the changed posted speed limits may no longer reflect the design speed. Difference between the design and posted speed impacts on road safety mainly from the lack of geometric design consistency and the associated conformance of geometric characteristics with drivers' expectations [18],[19]. This inconsistency when posted speed exceeds design speed can raise liability concerns even though drivers can safely exceed the design speed [42].

Traditionally, possible speed consistency treatments range from changing geometry through to the installation of advance warning signs that warn drivers of elements in the road corridor such as a curved section of highway [19]. Are these treatments appropriate in areas other than highways sections, perhaps in lower order roads where the differentials or inconsistencies are smaller? Cameron,(20) found that in urban areas, 26% of drivers were unaware of the speed limit and that these drivers were observed to be driving faster than others [11],[20]. Would warning signs be sufficient in these locations or perhaps the infrastructure cues weren't sufficient?

7. Operating speed

Whilst roadway geometry play roles in the design speed (the vehicle speed which a road is designed), the operating speed is determined from speeds actually selected by drivers. Operating speed is fundamental to the development of any roadway facility through geometric design element and used to determine an appropriate design speed [21]. Identification of the operating speed is fundamental to the development of any roadway facility [21] and not to be confused with the design speed which is often taken as the 95th percentile speed of free-flowing traffic expected to occur as a function of the adopted design standard of a road [43]. There is a circular argument with operating speed and design speed such that one should not be considered without the other. Generally, drivers make fewer errors at geometric features that conform with their expectations so that a consistent road design will help driver's select appropriate speeds or at their desired speed along the entire alignment [48]. The influence of other vehicles can impact on a desired speed and thus contributes to the operating speed.

In the absence of a known design speed, the operating speed of a road can be used as a basis to determine one for that section of a road section. The operating speed is typically taken as the 85th percentile speed (V85 km/h) which is defined as the speed at, or below, which 85 precent of vehicles are observed to travel under free flowing conditions past a nominated point [21],[23],[43]. This chosen speed by a driver when unhindered by other drivers, often assumed to be a road user's desired speed of travel, is considered to be operating under free-flowing conditions when there is at least 4 seconds headway between vehicles. The posted speed limit does influence the speed choice along with input from the road environment as explained earlier.

Operating speed is a common and simple measure of design consistency [23]. The difference between operating speed and design speed (V85–Vd) is a good indicator of the inconsistency at one single element, while the speed reduction between two successive elements (∆V85) indicates the inconsistency experienced by drivers when travelling from one element to the next [23]. A design speed should not be less than the intended operating speed and where the operating speed varies along the length of road, the design speed must vary accordingly [21]. Each road length is arguably unique and each element forming that corridor cannot be considered simply by a standard or the appearance [43]. Driver errors and crashes are more likely to occur when there is some disparity between what drivers may believe to be a 'safe' speed and the actual speed at which a feature can be negotiated safely [48]. Placing a sign that shows the speed limit does not automatically imply that drivers also choose the indicated speed [27] nor does it automatically imply that they will choose to ignore it. There is discussion that the operating speed should also be where there is no apparent attempt to overtake the vehicle ahead [43] but in reality, this is difficult to measure in-situ as it requires intensive qualitative measurements over and above the typical traffic counting devices.

The view that limits should be set at or close to the V85 speed dates back to the early 1940s in the USA with three main arguments put forward and repeated over the years [44],[45] as follows:

1. The collective wisdom argument: that V85 provides an objective basis for determining 'maximum safe speeds'.

The theory being that most drivers are capable of making good judgments about 'safe' driving speeds, and will in fact chose to drive at 'safe' speeds. On this basis the only role in setting the posted speed is to limit the speeds of the small minority of drivers who are incompetent or irresponsible [44],[45].

2. The speed dispersion argument: that speed limits near the V85 will minimise the variance of the speed distribution

Minimising the speed variance will minimise opportunities for vehicle conflict and therefore minimise the number of crashes. An important element of this argument is the proposition that setting speed limits lower than the V85 will lead to greater speed dispersion and in doing so will offset any benefits of lower speeds, and may actually increase crash rates [44],[45].

3. The enforcement practicality argument: that V85 limits have 'appeal' from an enforcement perspective, and represent a reasonable and realistic benchmark for enforcement.

This third argument is that enforcing speed limits below the 85th percentile requires a level of enforcement intensity and expense that has proven difficult to sustain [in the USA] [44],[45]. As mentioned previously, when designing road corridors, the inter-relation between operating speed and driver speed selection, or desired speed is not often clearly understood. Where the operating speed cannot be determined through speed measurement an operating speed 10 km/h higher than the posted speed limit is often adopted [21]. Or the reverse is true too. When speed limits are posted, often a figure of 10 km/h higher than the operating speed is adopted by the appropriate authority without truly understanding its impact. Where there is any doubt, the speed limit is rounded up. Unfortunately, practice will show that the driving community prefer a higher speed limit than lower. Factors such as travel time seem to have more influence than the perceived safety benefits.

Apart from the direct evidence that safety can be improved by setting limits below V85, the three arguments around the use of V85 in setting speed limits remains controversial [44] and been so for many years. Further research would help address this controversy and in doing so explore the relationships between the operating speed, the driver speed selection and driver behaviour. Would a critical review of the circular argument between operating speed and design speed change the way practitioners look at how speed limits are set?

8. Recommendations

Speed is an important factor in road safety and not only affects the severity of a crash, but is also related to the risk of being involved in a crash. With the link between speed, severity and risk of a crash it has been speculated that any reduction in speed as a result of changes to geometric elements will have a positive impact on road safety. Lane and shoulder width elements play a role in driver speed choice as empirical evidence generally suggests that narrower roads, and narrower lanes on roads, lead to slower travel speeds. This lower speed selection of drivers in turn leads to lower speeds and crash rate.

The literature review revealed that the effects of narrower cross-sections to lower speed choice, and associated crash rates, have been inconsistent and seem to be influenced by lane widths, shoulder widths and road types. Some researchers have concluded that reducing lane widths had no impact on speed selection at all. Similarly, the lack of geometric design consistency and the associated disparity with drivers' expectations has led to increased crashes rates where there is a difference between the design and posted speeds. Of note was the dated nature of a lot of the research and this in of itself highlights a need to provide more current data.

The majority of research though has focused on rural roads. This is expected, as the rural road environment is likely to be more homogenous than in urban areas where more complexity typically exists from more interactions of traffic, local circulation, access functions and inconsistencies of operating speeds.

It recommended that further research be undertaken with a focus on urban roads to resolve inconsistencies found in the literature. The research would contribute knowledge to understanding the effects on speed choice from specific geometric elements within a complex urban road environment.

Furthermore, the research would see to better understand the effects on speed choice from specific geometric elements within a complex urban road corridor. With a critical review of the circular argument between operating speed and design speed there is potential to change the way the certain geometric elements influence design and posted speed.

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