Principles of road design under a Safe System

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Abstract

The Safe System requires a paradigm shift in the way road designers and project managers think about road safety. Road designers, builders, operators and those that manage roads all have a key role in providing a road that is safe for all users.

This paper outlines various deficiencies in the traditional road design philosophy and proposes a new road design approach based on the Safe System. Key milestones in the evolution of international policy on the Safe System are outlined including its adoption as a guiding principle for the United Nations Decade of Action for Road Safety (2011-2020).

The traditional "blame the victim" approach is contested. The science behind the Safe System and "what works" is well established. This paper provides a brief summary of the key principles to designing a safe road. The next step is to ensure the systematic application of these principles in road design.

Keywords

Safe System, Road design

Introduction and approach

Road safety is an evidence-based process involving the systematic assessment and application of measures to create a road transport system that protects road users from fatal and serious injury. A Safe System is one in which all key elements of the road transport system (Roads, Vehicles and Speed) interact in a way that does not lead to death or serious injury. This requires a new approach to road design whereby road safety is fully integrated into the process. This is in contrast to the traditional approach whereby road safety is viewed as an "add-on" to the road design process in an effort to make the road "as safe as possible".

Whilst society as a whole has grown accustomed to the way roads look, it is important to remember that road design has been an evolving process rather than a revolutionary one. The first roads were spontaneously formed by humans and animals walking the same paths over and over in the pursuit of food and water (Lay, 1999). As towns and villages began to form, these paths became formal roads to facilitate the transport of goods. Not only did these early "tracks" evolve into the modern roads we now know, but they did so through an era where speed was of little concern or consequence.

One need only consider the absurd, yet widely accepted, situation now where society accepts driving on a single carriageway road with nothing more than a painted line to separate vehicles travelling in opposite directions at speeds in excess of 100km/h. The problem is that this type of road transport system is inherently unsafe; in this system it is a case of when, not if, a fatal or serious injury crash will occur. Yet, this has become such the norm that most road safety auditors would not raise this as a concern. Ultimately, road design has failed to keep up with vehicles that are now travelling at speeds far in excess of the human body's ability to withstand serious injury.

The purpose of this paper is to investigate how well Safe System principles are embedded in current road design standards and processes. A brief overview is provided on the Safe System and how it has evolved. The limitations of the traditional approach to road design are highlighted and then compared and contrasted with the Safe System. The key crash types that underlie the Safe System are discussed with a brief reference to the vehicle safety industry, noting how it has evolved from a fatalistic (blaming the user) approach to a model based on mitigating key crash types.

The paper recommends a set of principles to be integrated into road design guides to achieve a safe road. Practical examples are provided to illustrate the Safe System in practice.

The priority in designing and constructing a road must be that it is safe. The tools to achieve a safe road are well established. The challenge is to implement them systematically and on a scale large enough to bring about significant reductions in serious road trauma.

International policy on the Safe System

Growing international concern about the humanitarian toll associated with road trauma ultimately led to the first world report on traffic safety in 2004 (WHO, 2004). This was followed by an International Ministerial Conference on Road Safety hosted by the Russian Government in Moscow in 2009. The United Nations General Assembly later proclaimed the Decade of Action for Road Safety 2011-2020, which was officially launched in May 2011.

The Moscow Declaration (UN, 2009) acknowledged the findings of a report prepared by the International Transport Forum and the Organization for Economic Cooperation and Development - *Towards zero: ambitious road safety targets and the safe system approach* (OECD, 2008) - and its recommendation that all countries regardless of their level of road safety performance move to a safe system.

The Moscow Declaration then resolved to "Set ambitious yet feasible national road traffic reduction targets that are clearly linked to planned investments and policy initiatives and mobilize the necessary resources to enable effective and sustainable implementation to achieve targets in the framework of a safe system approach".

The Safe System underpins the Global Plan for the Decade of Action for Road Safety 2011-2020 (UN, 2011). The Global Plan calls for national activities under the Safe System pillar of Safer Roads to "Promote road safety ownership and accountability among road authorities, road engineers and urban planners by promoting the safe system approach and the role of self-explaining and forgiving road infrastructure".

RTA (2011) includes an overview of the Safe System and an historic account of its development. Key documents on the Safe System include the Organization of Economic Cooperation and Development's (OECD) report Towards Zero: Ambitious Road Safety Targets and PIARC's Road Safety Manual.

Traditional approach versus Safe System approach to road safety

While roads have been constructed since antiquity, it is only since the 1940's that post-war road construction expanded rapidly. The passing of the USA Federal-Aid Highway Act 1944 led to standardising the science of road design. While in the intervening years there have been numerous improvements in how roads are designed (Hasson, 2010 and Hasson, 2015), the core fundamentals remain: traffic flow and forecast growth; intersection type and design; geometric alignment and design; and pavement material and design (Rogers, 2002).

Shaheen sought to apply safety principles to the traditional approach. He identified the key design controls as: design speed; design vehicle; human factors; traffic volume; capacity and level of service; pedestrians and cyclists; and intersection and access control. He then introduced the significance of design speed on road user safety in terms of affecting injury severity outcome and discussed the concept of target speed, which seeks to use road engineering elements to influence travelling speed (Shaheen, 2014). This approach provides a greater appreciation of the impact of speed on safety but still relies on the traditional engineering design paradigm. Safety is not a leading object of design but a consequence of how design principles are applied.

In contrast, Hauer was critical of the engineering approach that sought to quantify human behaviour as a set of measurable factors. He observed that engineers are trained to manage inanimate objects whose properties are well known and can be quantified (Hauer, 1999). When a similar approach is used to define road user properties and the user does not behave as expected, it is seen as an uncontrollable outcome. Road safety professionals refer to this as "blaming the user". Under the Safe System the designer has a responsibility to design a road that is safe for all users acknowledging that user performance is limited. Hauer argues that road design should be based on road safety outcomes, such as "expected frequency of crashes or crash consequences", rather than using road safety proxies (Hauer, 1999), such as human factors.

Scandinavian research shows that even if all road users complied with road rules, fatalities would only fall by around 50% and injuries by 30% (Elvik et al., 2009). This is supported by comprehensive studies undertaken in South Australia which found that very few non-fatal crashes (3% metropolitan, 9% rural) involved extreme behaviour and, even in fatal crashes, the majority (57%) were due to system failures (Wundersitz and Baldock, 2011).

From an engineering perspective, the traditional approach to road safety is considered in terms favoured by economists as negative externalities, i.e. the unintended but unavoidable downside of an essential road transport system. Economists argue for the safest system that can be affordably achieved, based on a balance between the economic benefits of measures to reduce risk versus the cost required to implement these measures (cost-benefit analysis). These negative externalities are the equivalent of collateral damage (Johnston et al. 2014), i.e. the price we must pay as a society.

Acceptable levels of road safety are traditionally set based on the lowest level of risk that can be achieved at a reasonable cost. This approach forms the basis of the ALARP (As Low As Reasonably Practical) principle. ALARP was originally developed for industrial safety and is based on risk matrices that identify all possible risks, which are then systematically assessed in terms of probability and severity. Such an approach, when applied to the road transport system, focuses on risk of crashes rather than preventing injuries, assumes a level of collateral damage and is largely disregarded in any case in favour of a cost-benefit approach based on available funds. This leads to trade-offs being made between safety on one hand and mobility and access on the other.

For example, the UK's TD 19/06 Requirement for Road Restraint Systems and supporting Road Restraint Risk Assessment Process (RRRAP) uses a risk based approach to identify locations for safety barriers. Risks that are considered "tolerable" are treated using the ALARP principle, for which all reasonably practical efforts must be taken to lower the risk to "broadly acceptable". To define reasonably practical the "risk has to be weighed against the trouble, time and money needed to control or remove it" (DMRB, 2006). Clearly this is counter to Safe System principles and should not be considered acceptable when designing a road.

In contrast, the goal of the Safe System is to ensure that when crashes occur they do not result in death or serious injury. At the centre of the Safe System is the recognition that no-one should accept serious road trauma as an inevitable consequence of using the road.

Table 1. Traditional Approach versus Safe System (developed from Belin, 2012)

Traditional Approach	Safe System Approach
Focus on Crashes Aim to reduce risk of crashes	Focus on Injuries Aim to eliminate death and serious injury
Road user has primary responsibility	System designer has primary responsibility
Change individual road user behaviour	Change the environment (safe roads, safe vehicles, safe speeds). The system is designed according to human capability and human tolerance to crash forces
Safety is “optimised” once mobility and accessibility objectives have been achieved	Safety is a fixed parameter with threshold levels that cannot be exceeded. Mobility and accessibility are variables within this framework
Roads are made as safe as reasonably practical	Roads are self-explaining and forgiving of mistakes such that road users are protected from crash forces that exceed human biomechanical injury thresholds

A safe road in one that is self-explaining and forgiving of mistakes such that road users are protected from excessive crash forces. This requires roads and roadsides to be designed so as to reduce the risk and, most importantly, the severity of crashes.

Key crash types

The Safe System requires a focus on the key crash types that contribute to fatal and serious injury. While it is possible to identify multiple factors influencing crashes, and this exercise is useful in developing targeted countermeasures, it is also possible to identify just four groups of crash types that account for the vast majority of serious crashes resulting in death (Johnston et al, 2014). By changing the core road design assumptions to focus on these four (4) crash types the result will be substantially safer roads.

The key crash types that lead to death and serious injury are:

1. Head-on crashes;
2. Intersection crashes;
3. Run-off-road crashes; and
4. Vulnerable road user crashes.

In New Zealand 88% of high severity crashes and 90% of high severity injuries on rural roads are due to head-on, run-off-road and intersection crashes (NZTA, 2011).

In Australia (Australian Government, 2015), the following four key crash types represent 86.1% of fatalities (2013 data):

- Head-on crashes (17.7%);
- Intersection crashes (21.8%);
- Single vehicle run-off-road crashes (33.3%); and
- Pedestrian crashes (13.3%).

In the United States (NHTSA, 2015), the following four key crash types represent 86.6% of all fatal crashes (2013 data):

- Head-on crashes (9.3%);
- Angle crashes (17.9%);
- Crashes with fixed objects and rollover (42.3%); and
- Collisions with pedestrians and cyclists (17.1%).

These crash types represent the key focus areas for road designers and planners to ensure a safe road.

The importance of speed

The designer must understand the significance of speed in relation to each of the key crash types, as the human body’s tolerance to physical force is at the centre of the Safe System. The single most critical factor that determines the amount of force involved in a crash is speed. The amount of energy involved in a crash increases exponentially with speed:

KE = ½mv2

KE is Kinetic Energy; m is vehicle mass; and v is vehicle speed. Figure 1 illustrates the risk of fatality for the key crash types based on impact speed (RTA, 2011).

Human biomechanical injury tolerance for a pedestrian hit by a car will be exceeded if the vehicle is travelling at more than 30 km/h. Likewise, injury tolerance limits will be exceeded for the occupants of a vehicle involved in a head-on crash at speeds greater than 70 km/h; a side-impact crash at speeds greater than 50 km/h; and an impact with a tree or pole at speeds greater than 40km/h. Under a Safe System road users should not be exposed to impacts above the biomechanical threshold speeds (Johansson, 2009).

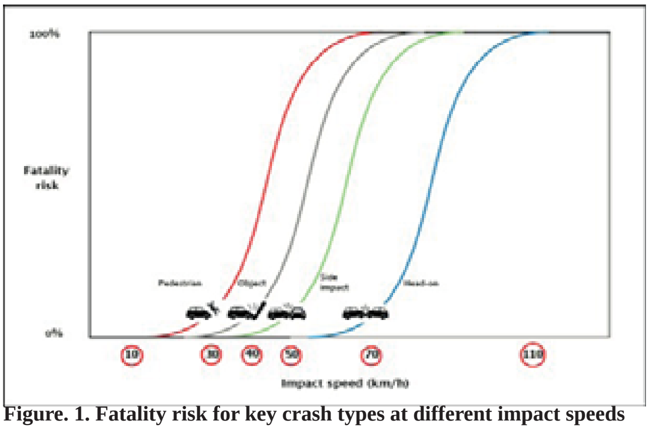

Figure. 1. Fatality risk for key crash types at different impact speeds (RTA 2011)

A brief look at the vehicle safety industry

It is interesting to briefly compare improvements to vehicle safety over recent decades. These improvements came about through a combination of litigation, advocacy and legislation (Gavin, 2012). Motor vehicle manufacturers originally argued that they “had no duty to manufacture a product that would be safe in collisions they had no direct part in causing”. However, the court ruled that they had a duty of care to ensure their design should not expose a vehicle occupant ‘to an unreasonable risk of injury in the event of an accident (Larson v General Motors, 1968 quoted in Gavin, 2012). Motor vehicles manufacturers were no longer able to blame the driver and were obliged to understand the risks associated with their product; and design safety features mitigating these risks.

A key step to testing and improving the design of vehicles was the introduction of the New Car Assessment Program (NCAP) in 1979 (Gavin 2012). NCAP produces a rating of one to five stars, with five stars indicating the highest level of protection within a vehicle’s weight class. Initial NCAP testing in the USA focused on frontal impact crashes (simulating head-on crashes) and later, in 1997, expanded to include side impact testing (simulating intersection type crashes).

The European New Car Assessment Programme (Euro NCAP) was founded in 1997 and includes a frontal test performed at 64 km/h into an offset deformable barrier, a side impact test performed at 50 km/h, a side impact pole test performed at 32 km/h and a range of pedestrian safety tests performed at 40 km/h. These tests simulate the four (4) key crash types (Figure 2).

NCAP was designed to provide safety information to the

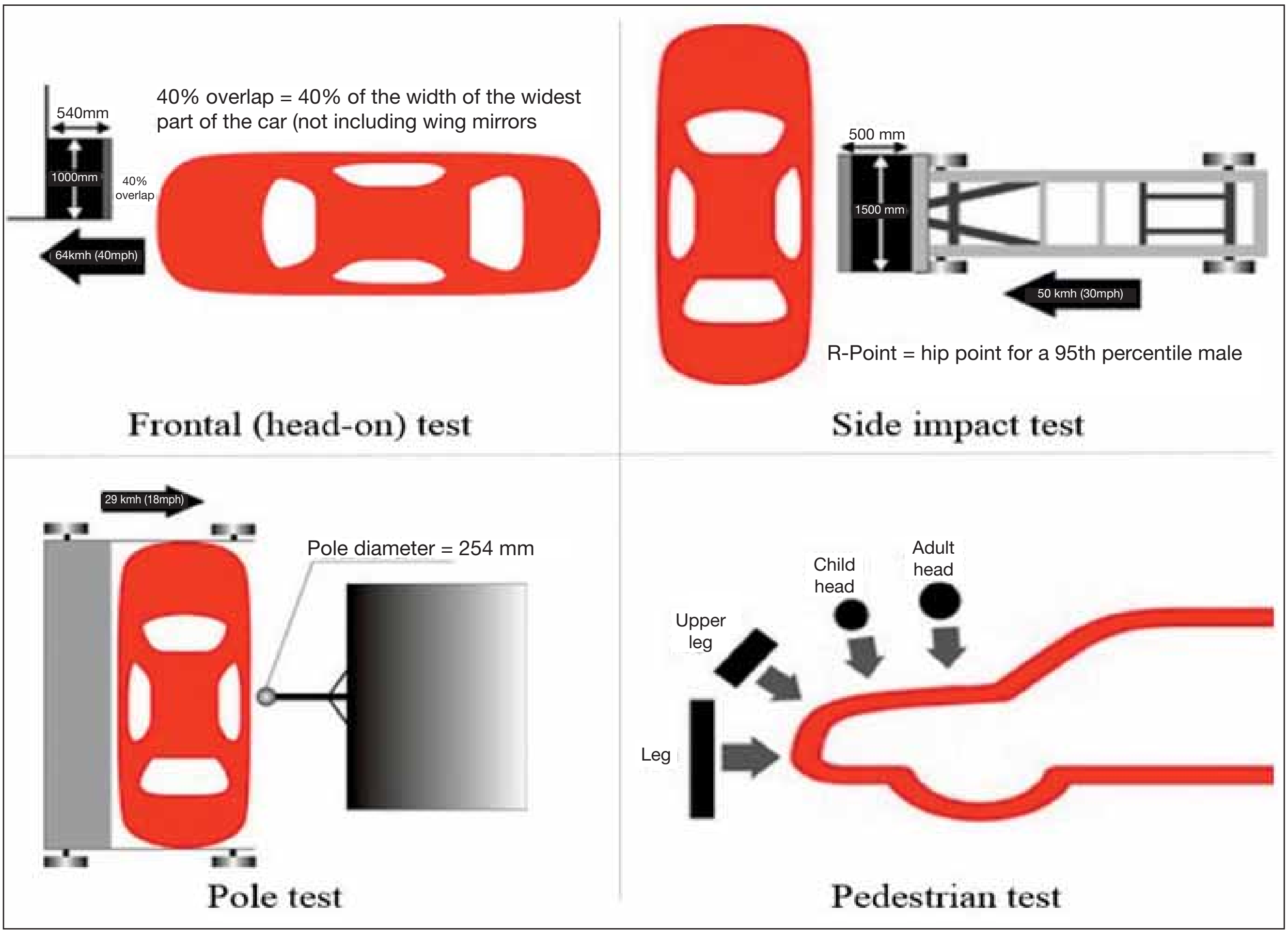

Figure 2. Euro NCAP testing protocols (Euro NCAP, 2016)

public and to improve vehicle safety by providing market incentives for vehicle manufacturers to improve safety. The testing protocols adopted by NCAP have driven substantial vehicle safety improvements in areas that are generally aligned with the four most common crash types that result in death and serious injury.

Principles of road design under a Safe System

“A road is a man-made product. In use, it is known to be harmful to health. It is not acceptable to produce roads and put them into use without providing for a premeditated amount of safety” (Hauer 1999). Hauer also argued that many design standards are based around proxies for safety rather than real safety effects (Hauer 1999). There is now sufficient research to quantify the safety benefits of individual road engineering elements (Austroads, 2012).

There are two ways to achieve a Safe System: either eliminate the potential for these crash types to occur through physical separation or reduce impact speeds at potential conflict points. The designer must consider the expected operating speed as well as the design speed and posted speed limit.

The designer also needs to understand the relationship between crash types, impact speed and severity, and use proven measures to manage them. To address the potential for right-angle crashes at intersections, for example, the designer must either design a safe intersection that eliminates these crash types or use proven methods to control speed. Changing the road environment to influence speeds by the use of road engineering measures is well established (OECD, 2006).

Measures to address head-on crashes include either median barriers to prevent potential conflicts or speed management to reduce impact speeds. Grade separation is an effective measure to prevent potential conflicts at intersections. At-grade intersections can be made safe through speed management and by reducing potential impact angles so as to reduce the transfer of energy in the event of a crash. Roundabouts, for example, require drivers to slow down and reduce potential impact angles. Roundabouts are considered an effective Safe System solution (OECD, 2008). There are multiple examples across the globe of well-designed roundabouts improving safety in very high-speed environments. Roundabouts are also an effective traffic calming solution in low speed residential areas and have a demonstrated safety benefit for all users, including pedestrians (Austroads, 2012).

Traffic signals should not be used in high speed (> 80 km/h) environments (Austroads, 2009). To mitigate the potential for high speed collisions at traffic signals, additional measures should be used to manage speeds, such as raised platforms, and to ensure compliance, such as combined red light and speed cameras.

Run-off road crashes are a major cause of serious road trauma on high-speed roads. Safe roadsides should incorporate measures such as a hardened recoverable space, full-length safety barriers and passively safe roadside furniture. Historically, clear zones have been preferred over road safety barriers, which are often regarded as a hazard. However, conventional assumptions about clear zone standards are being questioned (Larsson et al., 2003) and it is likely that roadside surface conditions may significantly contribute to rollover potential and affect the ability of a high-speed vehicle to regain control. It should also be recognised that full length safety barriers place less demand

Table 2. Safe System design principles to target key crash types

Crash Type	Safe Speed*	Prevention/Segregation	Mitigation/Inclusion
Head on Crashes	70 km/h	Median barriers	Limit potential impact speeds to 70km/h through speed management, particularly with enforcement using average speed cameras.
Intersection Crashes	50 km/h	Grade separation Close intersections Access control	Limit potential impact speeds to 50km/h through speed management and enforcement. Manage speeds and impact angles at intersections by treating with roundabouts and left turn only (drive on left) or right turn only (drive on right) intersections.
Run-off Road Crashes	40 km/h	Remove roadside hazards Provide protection using road safety barriers (road safety barriers may be required even when roadside hazards are removed to prevent rollover, particularly in soft, sandy or uneven roadside conditions)	Install passively safe (frangible/energy absorbing) roadside infrastructure or limit potential impact speeds involving roadside furniture to 40km/h through speed management and enforcement
Pedestrian Crashes	30 km/h	Pedestrian bridges and underpasses Segregated pedestrian/cycle paths protected from vehicles by safety barriers	Limit potential impact speeds to 30km/h through speed management and enforcement

* Road users should not be exposed to impact speeds exceeding these levels

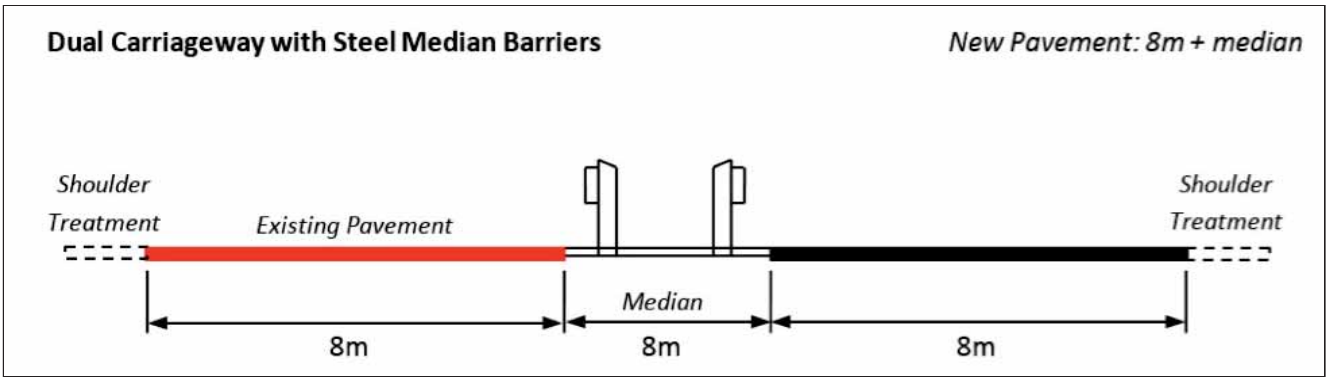

Figure 4. Route 55 upgraded cross section

on road cross-section compared to wide clear zones or wide medians. This can lead to a lower project cost and have a significantly less impact on the environment.

To address the safety of vulnerable users such as pedestrians and cyclists, the designer must identify the function of the road and the likely operating speed of vehicles. The designer must then consider pedestrian facilities that either provide adequate separation from vehicles or implement an effective speed management strategy that ensures no pedestrian will be hit at speeds exceeding the injury threshold. Pedestrian fencing is an effective measure (Austroads, 2012) to direct pedestrians towards safe facilities, noting that if facilities are positioned correctly on desire lines, the need for pedestrian fencing can be minimised. Pedestrian fencing is also an effective measure to prevent pedestrians from entering or crossing higher speed roads.

It is also important that road designers are engaged with enforcement agencies to ensure that effective enforcement measures are integrated into the road design and planning process. There are many proven benefits to automated enforcement measures (Austroads, 20121 & Austroads, 2004). For example, automated average speed or point-to-point speed enforcement systems should be considered as standard features on high speed Freeways. Similarly, consideration should be given to fitting combined speed/red light cameras as standard features on traffic signals, particularly in higher speed environments.

Safe System Design Principles

A safe road design requires the designer to address the following questions:

(a) Is it possible to have a head-on crash at speeds greater than 70 km/h?

(b) Is it possible to have a right-angle crash at speeds greater than 50 km/h?

(c) Is it possible to have a side-on crash with non-frangible object at speeds greater than 40 km/h?

(d) Is it possible to have a pedestrian or cyclist crash at speeds greater than 30 km/h?

An affirmative response to any of these questions means that the Safe System is violated. If this is the case, the designer should seek to move towards a Safe System compliant design using the key principles outlined in Table 2.

It may be argued that the principles of Safe System design are easier to apply to a new road design. However, the same principles can be applied through remedial works to an existing road. This is common practice as part of extended design domain or brownfields design guides which can be applied incrementally as remedial road safety improvements (Levett, 2009).

Case Study 1: Route 55 (Qatar)

Prior to 2013, Route 55 was a two lane single carriageway road with a history of serious crashes. The types of crashes were consistent with those expected for a high speed rural road, i.e. head-on crashes, run-off-road crashes and intersection crashes.

Figure 3. Route 55 before it was upgraded

Following a multiple fatality head-on crash in 2012, there was an urgent call to improve the safety of the road. As a result, the road was upgraded to four lanes with an 8 metre wide median together with median barriers to separate opposing traffic (two lanes in each direction) and expected to operate at high speed. The upgraded cross section is shown in Figure 4.

Figure 5. Route 55 after the upgrade

All minor accesses and intersections were reconfigured to a right in/right out layout and all left-turn and U-Turn movements were directed to roundabouts at approximately 5 to 10km spacing.

Figure 6. Before – intersection with risk of high severity turning crashes

Figure 7. After – intersection converted to Right In/Right Out configuration

The Route 55 upgrade has virtually eliminated the potential for head-on crashes, through the use of median barriers, and significantly reduced the potential for high severity intersection crashes, by managing all turning movements at roundabouts. While further refinements could have been made, such as the provision of 1 to 1.5 metre-wide paved shoulders to mitigate run-off-road crashes, this project represents a good example of Safe System adoption. Moreover, it represents a very good demonstration project for other rural roads in Qatar.

Case Study 2: Centennial Highway (New Zealand)

A spate of fatal crashes on Centennial Highway near Wellington, New Zealand in the late 1990's and early 2000's sparked significant public concern (Marsh, 2010). In response, various traditional road safety remedial measures were implemented including upgraded warning signs and extra wide profiled (tactile) centreline markings. These measures were considered to be a success for two years; that is until another two fatal head-on crashes occurred in 2004.

As a result, the speed limit was lowered from 100km/h to 80km/h and a narrow median wire rope barrier installation was implemented (Figure 8).

Figure 8. Centennial Highway

Prior to the median barrier installation there were 12 fatal crashes and four serious injury crashes (1996 to 2004) at an average annual social cost of $5, 796,899. From 2004 to the end of the evaluation period (2009) there were no fatal or serious injury crashes and the average annual social cost reduced to $65,400. Analysis of surveillance videos obtained from CCTV cameras installed along the length of the project indicated that vehicles involved in crashes with the wire rope barrier generally sustained very minor damage and were, in many cases, observed to drive away after impact.

This case study highlights the limitations of a traditional approach to road safety and demonstrates how serious road trauma can be significantly reduced through the adoption of Safe System principles.

Discussion

Under the traditional road design paradigm, safety is not a leading object of design but a consequence of how design principles are applied. The safety of road users should not be reduced to what is considered reasonably practical, where risk is weighed against the trouble, time and money needed to control or remove it. Serious road trauma should not be viewed as an inevitable consequence of using the road.

The principles of segregating conflicts in the transport system and managing impact speeds are universal, that is, they are valid in any country. In a Safe System it is accepted that crashes will occur, but it is not accepted that road users will be killed or seriously injured as a result. The Safe System requires a paradigm shift in the way system designers think about road safety. System designers must recognise and understand human capabilities and injury tolerance constraints as a basis for developing a transport system that protects road users from fatal and serious injuries.

The principles of Safe System design apply to the construction of new roads as well as the retrofitting of remedial works to existing roads. The science behind the Safe System approach and “what works” is well documented and is continuously being refined. The next step is to ensure the systematic application of these principles in road design.

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