MODELING AN INFRASTRUCTURE SAFETY RATING FOR VULNERABLE ROAD USERS IN DEVELOPING COUNTRIES

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DEDICATION

To François Dahdah (1977-1993)

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ABSTRACT

The need for increased road safety measures is undeniable, given that well over a million people die every year in road crashes worldwide. The majority of fatalities are suffered in low and middle income countries. While road crash fatality rates steadily decrease in high income countries, road traffic crashes and injuries continue to increase both in absolute numbers and relative terms in low and middle-income countries. Unless appropriate action is taken urgently, the problem will worsen. Such accidents cause serious public health and development issues, tax health care systems, and strain already limited resources.

At particular risk of injury or death are the Vulnerable Road Users (VRUs), such as pedestrians, non-motorized vehicle users, and two-wheeler users. These VRUs are one of the main reasons for the disparity between high and lower-income countries. For the first time, a safety performance indicator for infrastructure safety is developed and used in low and middle-income countries. The model is test piloted and calibrated in several low and middle-income countries by the International Road Assessment Program (iRAP).

The relationship between the risk of a pedestrian being seriously injured when hit by a vehicle and impact speed is not continuous and two constant risk areas are observed for the ranges of impact speed between 15-30 km/h and 35-45 km/h. The risk increases exponentially between 35 and 55 km/h. Those findings are observed in the database analyzed and validated through simulations.

The safety performance indicator developed in this study explains about 50% of the variation in the fatality rate for pedestrians.

Fences that are commonly used in East Asia to provide separation between motorized and non-motorized traffic are not effective unless they are properly anchored to the ground.

A rule of thumb of 70 times the gross domestic product per capita is derived through analysis to be the estimate of the value of statistical life to be used in developing countries to value life in road safety.

The conventional value of serious injury being 10% the value of statistical life used in some developed countries is found not to be valid when valuing a serious injury in developing countries. An average value of serious injury equal to 25% the value of statistical life is derived in this study and recommended for developing countries.

The World Bank does not have a systematic approach to ensure the safety of the roads that are parts of the Bank's transport portfolio (around $ 4 billion per year). The Bank also lacks a tool for guiding the decision-making process to identify safety improvement needs and for developing a system-wide program of site-specific improvement projects. This research addresses this critical need and the results can be used as a tool in the appraisal phase of the World Bank financed transport projects.

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List of Acronyms

ADB	Asian Development Bank
AIS	Abbreviated Injury Scale
AMF	Accident Modification Factor
AusRAP	Australian Road Assessment Program
BSM	Black Spot Management
CDF	Cumulative Distribution Function
CVS	Crash Victim Simulation
DALY	Disability Adjusted Life Year
DoE	Design of Experiment
EuroNCAP	European New Car Assessment Program
EuroRAP	European Road Assessment Program
FARS	Fatality Analysis Reporting System
GDP	Gross Domestic Product
HC	Human Capital
HIC	Head Injury Criteria
HSM	Highway Safety Manual
IHSDM	Interactive Highway Safety Design Model
iRAP	International Road Assessment Program
LTV	Light Trucks Vehicles
MADYMO	Mathematical Dynamic Models

MAIS	Maximum Abbreviated Injury Scale
NASS	National Automotive Sampling System
NHTSA	National Highway Traffic Safety Administration
NSM	Network Safety Management
OECD	Organization for Economic Cooperation and Development
PCDS	Pedestrian Crash Data Study
PIARC	World Road Association
RIA	Road Safety Impact Assessment
RPPS	Road Protection and Prevention Score
RPS	Road Protection Score
RSA	Road Safety Audit
RSI	Road Safety Inspection
RSM	Road Safety Manual
SPI	Safety Performance Indicator
UN	United Nations
USDOT	United States Department of Transport
UsRAP	United States Road Assessment Program
VMT	Vehicle Miles Traveled
VRU	Vulnerable Road User
VSI	Value of Serious Injury
VSL	Value of Statistical Life

WHO	World Health Organization
WTP	Willingness to Pay

CHAPTER 1

INTRODUCTION

1.1 Global Health Losses From Road Traffic Injuries

The first automobile crash-related injury was reportedly suffered by a cyclist in New York City on May 30, 1896. The first fatality, a pedestrian in London, occurred a few months later (August 17) (Road Peace, 2003). The World Health Organization data show that in 2005 nearly 1.3 million people worldwide died as a result of road traffic injuries and the projections for the years 2015 and 2030 are 1.6 and 2.1 million deaths respectively (Mathers and Loncar, 2005). In addition to these deaths, between 20 and 50 million people globally are estimated to be injured or disabled each year (McGee, 2003).

According to the WHO Global Burden of Disease Project, road traffic injuries were the second leading cause of death worldwide among children aged 5-14 and young people aged 15-29 in 2002. The scale of road traffic deaths is similar to tuberculosis and malaria (Table 1-1).

During the year of 2005, the overall mortality rate was 20.4 per 100,000 populations (see Table 1-2). Low and middle-income countries had a rate much greater than high-income countries (21.7 vs. 12.3). The vast majority – 91% - of road traffic deaths were in low and middle-income countries. Only about 9% of road traffic deaths occurred in high-income countries. It is projected that 94% of road traffic deaths will occur in low and middle-income countries in 2015 with a rate of 25.1 deaths per 100,000 populations compared with a rate of 10.7 in high-income countries. The performance gap between rich and poor countries is widening as it is shown in Table 1-2.

Table 1-1: Twelve Leading Cause of Mortality in Low and Middle-Income Countries

RANK	DISEASE OR INJURY	PROPORTION OF TOTAL (%)
1	Ischaemic heart disease	12.4%
2	Cerebrovascular disease	10.0%
3	Lower respiratory infections	6.7%
4	HIV/AIDS	5.6%
5	Chronic obstructive pulmonary disease	5.4%
6	Perinatal conditions	4.6%
7	Diarrhoeal diseases	3.4%
8	Tuberculosis	2.8%
9	Road traffic injuries	2.4%
10	Childhood-cluster diseases	2.0%
11	Malaria	1.8%
12	Diabetes mellitus	1.8%

Table 1-2: Projections for Global Road Traffic Deaths for the Years 2005-2030

Estimated global road traffic injury-related deaths in 2005			
	Number	rate per 100 000 population	Proportion of total (%)
Low and middle-income countries	1,196,495	21.7	91%
High income countries	116,557	12.3	9%
Total	1,313,052	20.4	100%

Projected global road traffic injury-related deaths for 2030			
	Number	rate per 100 000 population	Proportion of total (%)
Low and middle-income countries	2,029,308	29.3	96%
High income countries	82,784	8.3	4%
Total	2,112,092	26.7	100%

These projections estimated that road traffic deaths will increase by about 69 % between 2005 and 2030 in low and middle-income countries, while it will decrease by about 29% in high-income countries for the same period.

The number of people being killed and projected to be killed in the future represents only a fraction of the human loss and suffering inflicted by road crashes. Using epidemiology evidence from national studies, a conservative estimate can be obtained of the ratios between road deaths, injuries requiring hospital treatment, and minor injuries as being 1:15:70 in most countries. In many low and middle income-countries, the burden of traffic related injuries is such that they represent between 30% and 86% of all trauma admission (Odero, 1997).

The overall health burden of any injury-related incident is measured in Disability Adjusted Life Years (DALYs). One DALY is equal to one year of healthy life lost, either due to premature death or disability.

In low and middle-income countries during 2005, road traffic injuries were the ninth leading cause of disability-adjusted life years lost, accounting for around 40 million DALYs lost (Figure1), or 3% of the global burden of disease.

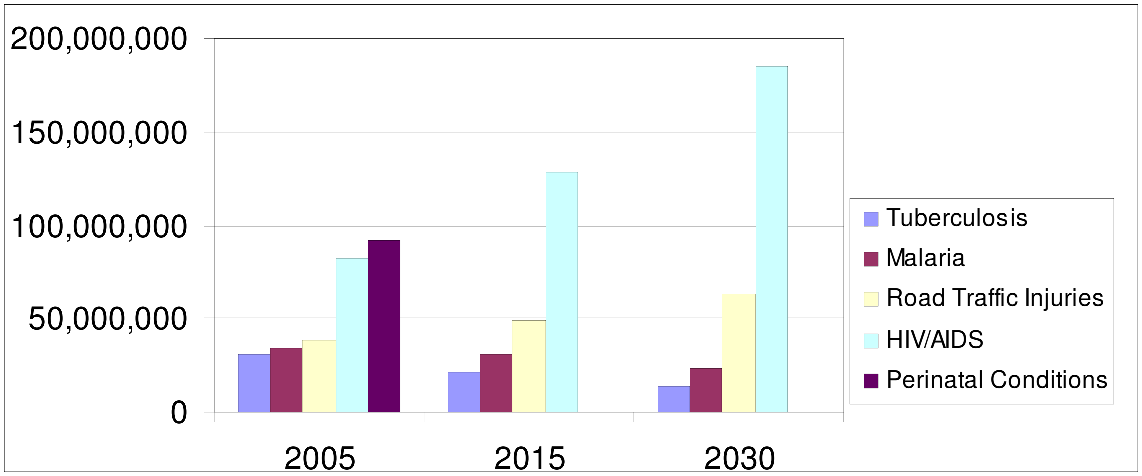


Figure 1-1: DALYS in Low and Middle-Income Countries (Total Population)

According to the latest forecasts by the World Health Organization (Mathers and Loncar, 2005), road traffic injuries will be the first leading cause of DALYs for children aged 5-14 and the second leading cause of DALYs for young males aged 15-44 (after HIV/AIDS) by 2015 in low and middle-income countries (Figure 1-1).

The magnitude of road traffic injuries in low and middle-income countries can be summarized as follows:

- In 2005, around 1.2 million people are killed as a result of road traffic injuries
- Road traffic injuries were the 9th leading cause of death and DALYs in 2005.
- Some 90% of road traffic deaths occur in the developing world, which comprises two thirds of the global population
- As motorization increases, many low and middle-income countries will face a growing toll of road traffic injuries, with devastating human, social, and economic consequences.
- Economically active adults, aged 15-44 years, account for more than half of the road traffic deaths
- Road traffic deaths will increase by about 69 % between 2005 and 2030 in low and middle-income countries

- Without new or improved interventions, road traffic injuries will be first leading cause of DALYs for children aged 5-14 and the second leading cause of DALYs for young males aged 15-44 (after HIV/AIDS) by 2015

1.2 A Problem for Vulnerable Road Users

Although all types of road users are at risk being injured or killed in a road traffic crash, there are notable differences in fatality rates between road users groups. In particular, the "vulnerable" road users (VRUs), such as pedestrians, non-motorized vehicle users, and two-wheeler users are at greater risk than vehicle occupants and usually bear the greatest burden of injury. This is obvious in low and middle-income countries because of the greater variety and intensity of traffic mix and the lack of separation from other road users. Of particular concern is the mix between slow-moving and vulnerable non-motorized road users, as well as motorcycles, and fast-moving motorized vehicles.

Estimates of the number of road deaths and injuries can vary due to limitations of injury data collection and analysis, underreporting, and differences in interpretation. However, VRUs remain the majority of the traffic related deaths and injury in any sample of data collected in developing countries.

The Asian Development Bank report on VRUs in the Asian and Pacific Region, published in 1996, shows that VRUs form the majority of road traffic related injuries and fatalities. VRU fatalities in Asia constitute 50%-90% of the total number of fatalities. Data from Africa (Figure 1-2) shows more pedestrian fatalities than motorcyclists. This is mainly due to income level in those countries, as the poorest people tend to be pedestrians. As income level rises, people start using motorcycles as is the case of Eastern Asian countries.

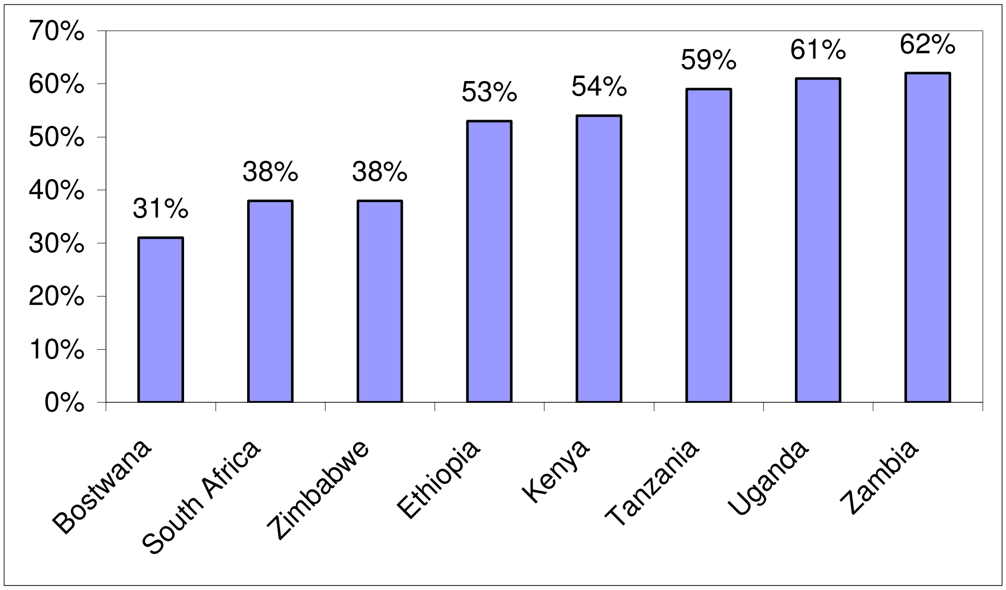


Figure 1-2: Vulnerable Road Users' Crash Related Fatalities as a Percentage of Total Crash Fatalities, (USDOT, 2000)

Pedestrians are the most common victims of traffic crashes in many parts of the world (Odero, 1007). In 1995, pedestrians represented 20 percent of traffic fatalities in the United States and Europe, but represent 42 percent in Asia, 45 percent in Africa, 51 percent in the Middle East, and 60 percent of traffic fatalities in Latin America (Guitink*, 1995*). Studies of individual countries verify these estimates (Mohan, 2002; Peden*, 2004).*

The 2007 WHO Mortality Database (WHO Database) provides data on deaths by gender and age by approximately 10,000 different causes (using International Classification of Diseases (ICD), including pedestrian and bicycle traffic crashes. The deaths are registered and causes of death are coded by authorities in each country. Each participating country also provides population data so that the mortality data can be normalized.

The WHO Database includes transportation fatality data from 78 countries, but the amount and completeness of the data varies. Therefore, the analysis focused on the 50 countries with the most numerous and reliable transportation fatality data. This included all countries that reported at least 100 transportation fatalities and reported a specific cause for at least 90% of these fatalities (e.g., countries with less than 10 percent of causes coded as “unknown”). For countries with multi-year data, data from the most recent year were used. The coding of causes in the “other non-motorized” crash category may not be consistent between countries. For example, more than 90% of the fatalities in Uruguay and El Salvador are in this category, and very few crashes are in the “pedestrian” and “automobile” categories. This modal distribution is unlikely.

Many countries have high percentages of pedestrian and bicycle fatalities. According to the WHO Database, pedestrians represent more than 30% of transportation fatalities in Japan, Mexico, Colombia, Poland, Uzbekistan, Chile, Ecuador, Cuba, Israel, Hong Kong, Paraguay, Slovakia, Puerto Rico, Lithuania, Panama, Latvia, Estonia, and Trinidad, and Tobago. Bicyclists account for more than 10% of transportation fatalities in Japan, Poland, The Netherlands, Cuba, Hungary, Slovakia, Denmark, Finland, and Lithuania.

It is likely that high pedestrian and bicycle fatality percentages are related to high levels of walking and bicycling in particular countries. While more information about use levels is needed to evaluate the relative safety of each mode, the high percentages of fatalities to VRUs indicate that pedestrian and bicycle safety are critical issues in many countries. Figure 1-3 shows the crash fatalities compositions by transportation mode in several low and middle-income countries. Notably, China and India, the largest countries in the world, have not provided fatality statistics for the database.

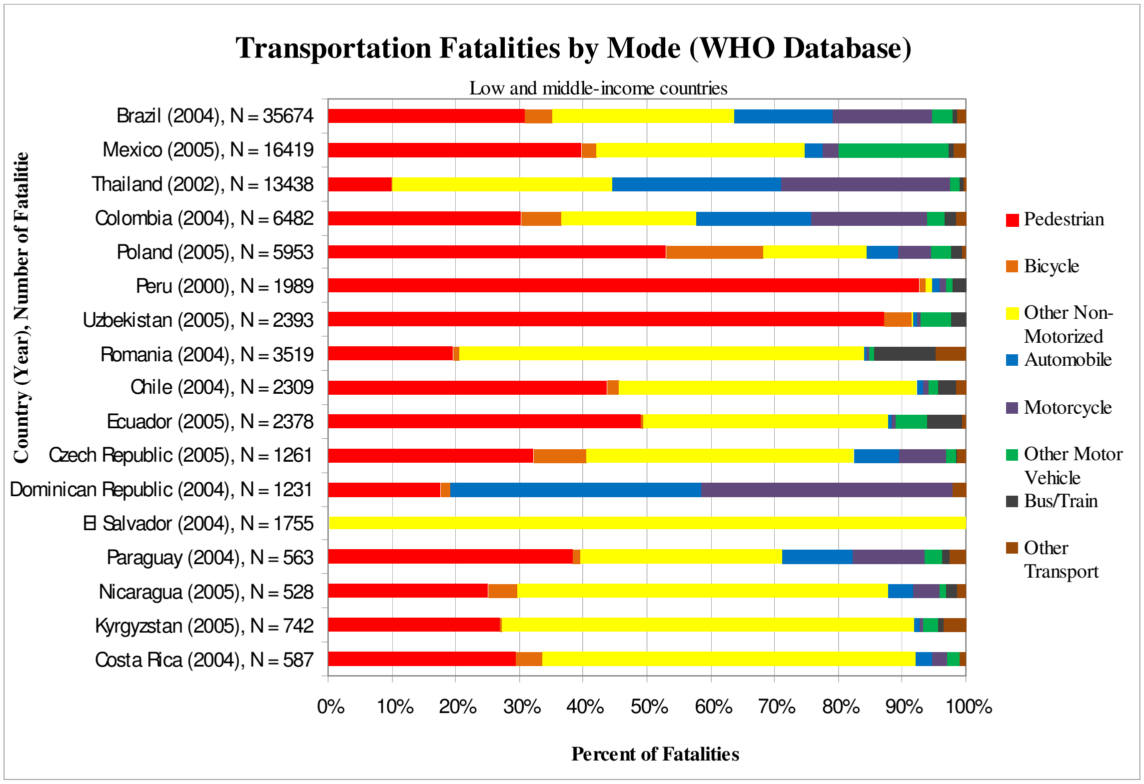


Figure 1-3: Transportation Fatalities by Mode, (WHO MORTICD 10 Database, 2007).

Several general conclusions can be drawn from the WHO and UNECE fatality databases and other sources of international pedestrian and bicycle safety data.

- Pedestrians are the most common or second-most common type of fatal traffic crash victims in nearly all countries. While there are variations between databases, the prevalence of pedestrian fatalities is high regardless of the source. This underscores the serious problem of pedestrian injuries and importance of developing policies, programs, and projects to improve pedestrian safety.

- Urban areas tend to have a greater percentage of reported pedestrian fatalities than countries as a whole. Pedestrians represent more than 50% of traffic fatalities in many cities. This may occur because cities are areas with greater pedestrian activity and mixed pedestrian and motor vehicle traffic. Bicycle fatalities vary widely between communities. This is likely to be related to the amount of bicycling and the quality of bicycle facility networks in each country and city. However, bicyclists represent more than 15% of all fatalities in several communities.
- Pedestrian and bicycle injuries are often significantly underreported in police databases. The actual number of pedestrian and bicycle injuries that occur may be 2 to 10 times greater than shown by police crash reports (for severe injuries). Undercounting reduces the ability of local jurisdictions, national governments, and the world community to prioritize and implement improvements for non-motorized transportation safety.

1.3 Road Safety Policies

1.3.1 Evolution of Road Safety Paradigms

Progress in the area of road injury prevention is formulated in an environment of beliefs, called *paradigms*, as can be seen in the next table. Some of them are professional folklore, *i.e.* a widely supported set of beliefs with no real basis. For example, the “accident-prone driver” was a belief that was supported by the data in the sense that a small number of drivers do participate in a disproportionate number of accidents. It follows that the identification and removal of these drivers will reduce crashes. A more scientific analysis of the data indicates that this phenomenon can be explained simply by the random nature of the accidents, and not for a specific error-prone attitude of such drivers.

In the 1950s the approach in road safety management was to blame the driver in what is called “The nuts behind the wheel” model where there was no shared responsibility.

In 1968, William Haddon Jr. developed a matrix of categories to assist researchers trying to systematically address injury prevention. The idea was to look at injuries in terms of causal factors and contributing factors, rather than just using a descriptive approach. The matrix divided these factors into human factors, vehicle factors, and environmental factors. Each factor was then considered in a pre-event phase, an event phase, and a post-event phase.

Haddon described a new approach to the epidemiology, prevention, and amelioration of trauma which was based on the transition to approaches etiologically rather that descriptively based (Haddon, 1968). He stated that there is a common and universal fallacy in this field, which is the assumption that the priority rank of countermeasures in terms of their ability to influence the end results of concern must parallel the ranking in order of their relative contributions of causes influencing those results. More simply, it states that because drivers cause most accidents, programs correspondingly must be concerned with drivers. In the real world, there is no basis for making this assumption as it leads to demonstrably false conclusions.

Haddon, for the first time, noted the importance of (Haddon, 1980) separation in space and time of the energy being released from susceptible structures, whether living or inanimate. This strategy includes the use of sidewalks and the phasing of pedestrian and vehicular traffic, the elimination of vehicles, and their pathways from community areas commonly used by children. This strategy has as its hallmark the elimination of intersections of energy and susceptible structure – a common and important approach. This strategy will be one of the fundamentals in the Swedish Vision's Zero policy developed in 1997.

In the 80's and 90's, countries began adopting targeted national plans which give more focus on result measurements in terms of number of fatalities and injuries. This management system is still largely used in many countries. For example, the EU aims to reduce their fatalities by 40% for 2010 and the USA aims at no more than 1.0 fatality per 100 million vehicle miles traveled (VMT) by 2008, compared with the 2005 rate of 1.5 Finland had a 65% of reduction in fatalities for 2005. Cost-benefit analysis was introduced in appraisal of transport projects in developed countries during that period.

Since late 90's, some developed countries that have the best record in traffic safety, started adopting different management systems that focus on accountability and shared responsibility between the user, the designer, and the operator. These systems aim to manage the kinetic energy across road/vehicle/user interface. This approach created the switch from reducing crashes to preventing casualties (fatalities and serious injuries).

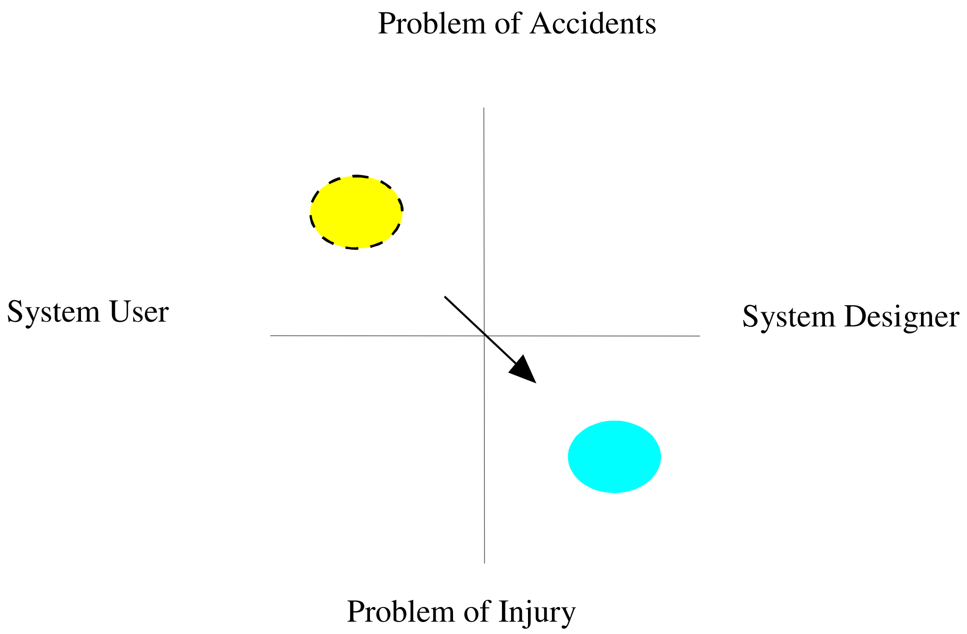


Figure 1-4: From Crash Reduction to Injury prevention

1.3.2 Systems Approach in National Road Safety Policies

Modern Road Safety makes a distinction between the situation and the management systems necessary to control it, with prevention activities that largely exceed the self-evident fields of the traditional *3 E* (Engineering, Enforcement, Education) approach, first introduced in 1925. Modern Management systems aim to be inclusive, *i.e.* to include explicitly all activities part of such system.

Road deaths and injuries can be avoided by adopting a culture of safety involving all key participants and implementing important safety measures widely and systematically. This “Systems approach” recognizes that road safety is a responsibility shared amongst all road safety stakeholders (Figure 1-5). The vehicle manufacturer has a responsibility to provide crash protection inside and outside the vehicle. The vehicle uses a road system where conflict is minimized by design and energy transfer is controlled as much as possible. That system is then used by a community that complies with risk-avoiding behavioral norms created by education, legislation, and enforcement. Road designers and builders are an integral part of the systems approach to road safety.

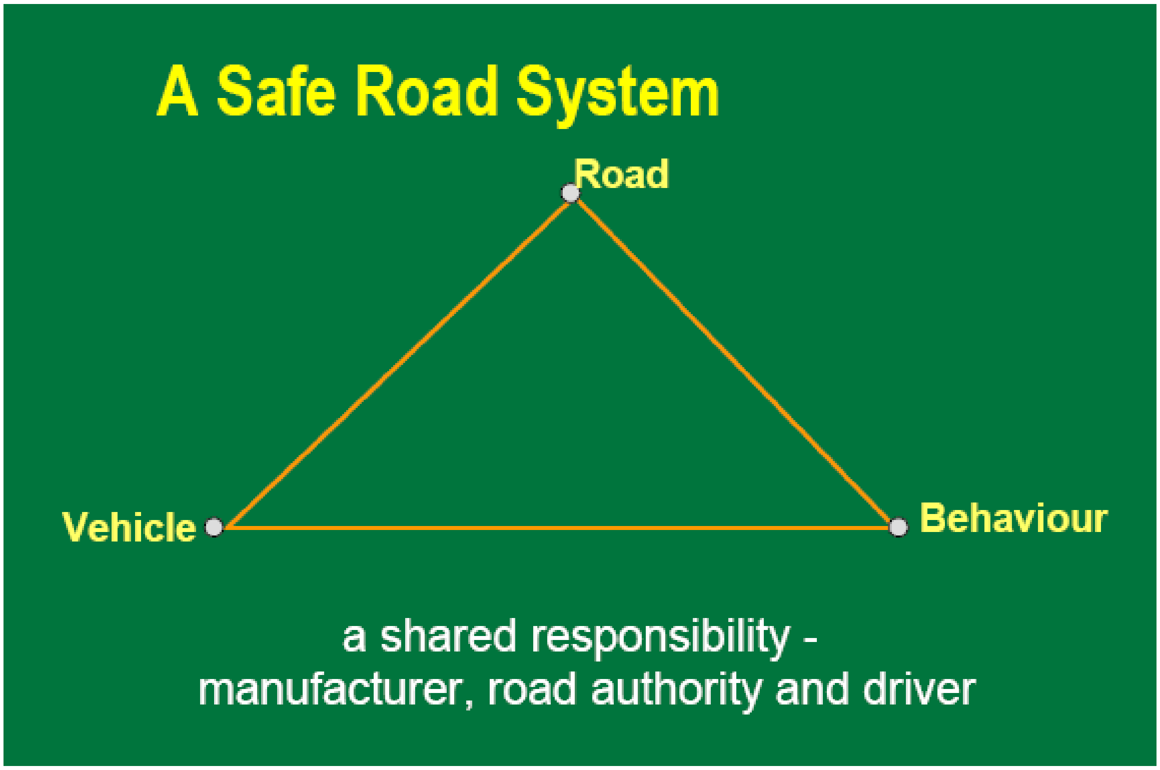


Figure 1-5: The “Systems Approach” in Road Safety – as Shared Responsibility

Both Sweden and the Netherlands have formally adopted the systems approach. They have implemented legislation models in which effective partnerships are the key method of delivering road safety plans, setting targets, and introducing other safety performance indicators. (See Appendix A)

1.4 Road Safety Management Systems

The road safety management system can be viewed in terms of three essential elements as described in the World Bank's Transport Note TN-1 (Bliss, 2004):

- Institutional management functions
- Interventions
- Results

The conceptual framework for describing the road safety management system has been refined over recent years. The management system as described in the Road Safety Strategy 2010 in New Zealand, uses an "outcome management" framework (Figure 1-6) that links what we do (output) to what we are trying to achieve (outcome), and focuses attention on providing the safest possible road network.

Social cost is the aggregate measure of all costs that crashes inflict the community. It includes not just material losses, but also pain and suffering. Final outcomes consist of fatalities and serious injuries. They are what we seek to avoid and are the main components of social cost.

Intermediate outcomes are not desired for themselves but for what they entail; better final outcomes. They include average traffic speed, the proportion of drunk drivers, the seatbelt wearing rate, the physical conditions of the road network, and the standard of the vehicle fleet. Intermediate outcomes are measured easily and are generally reliable indicators of how well our safety interventions are working.

Outputs represent physical deliverables, such as the number of police patrols and the amount of advertising delivered. Alternatively, they correspond to milestones showing that a specified task has been completed.

A slightly updated version of this management system was presented in the Sunflower study (Koornstra *et al.,* 2002). The intermediate outcomes are called "performance indicators" and outputs are replaced by "Safety measures and programs". Structure and culture form the base of the hierarchy (Figure 1-7).

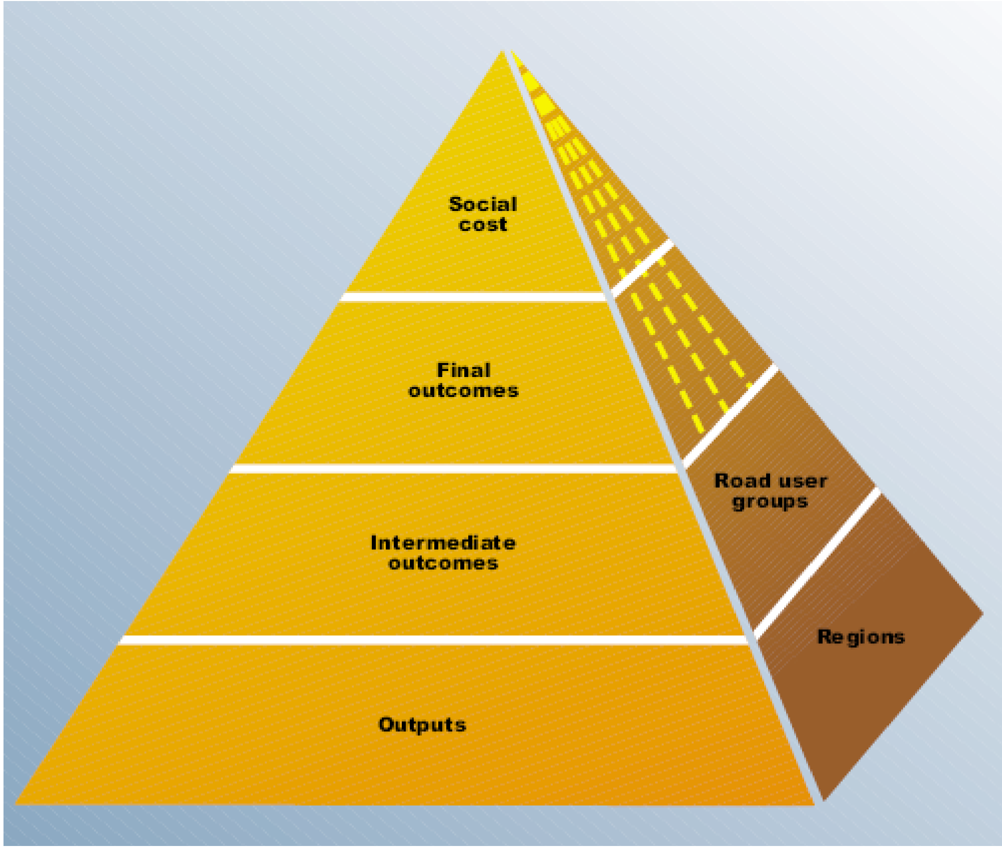


Figure 1-6: Outcome Hierarchy, (National Road Safety Committee, New Zealand, 2006)

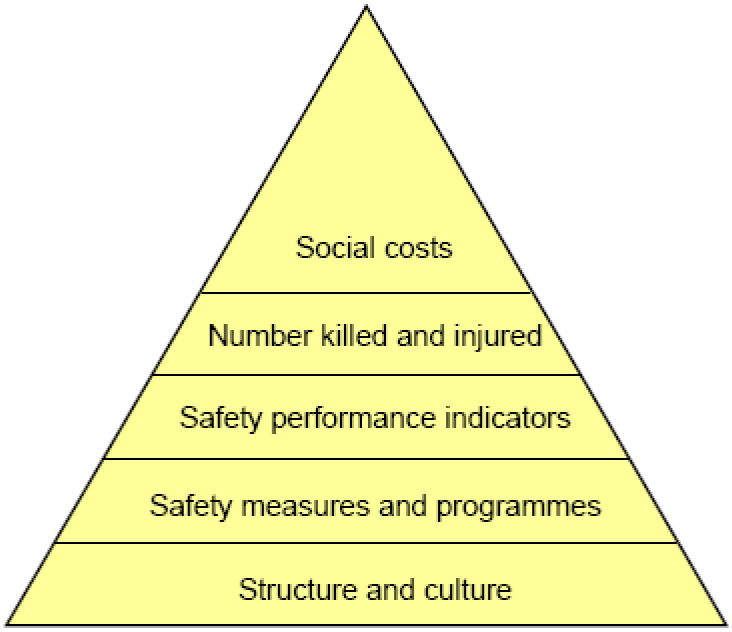


Figure 1-7: A Target Hierarchy for Road Safety (Koornstra *et al.,* 2002)

Bliss (2004) identified seven vital institutional management functions to carry out “Results Focus” road safety management system. These functions are:

- Results focus
- Coordination
- Legislation
- Funding and resource allocations
- Promotion
- Monitoring and evaluation
- Research and knowledge transfer

In low and middle-income countries, a road safety results focus is usually absent. Targets are rarely set and little is known about the effectiveness of interventions, given the absence of reliable performance data. Agencies are rarely held to account for safety results that fall within their sphere of responsibility and influence.

Deficiencies are also evident in safety interventions. Standards and rules governing the safety of roads, vehicles, and road users are often fragmented and not based on best practice. Institutional implementation arrangements remain the biggest impediment to progress. Funding and legislation are usually poorly matched to the task of improving road safety nationwide. Coordination arrangements are often ineffective and hampered by limited agency accountability for achieving safety results. Monitoring and evaluation of safety performance is at best superficial (Bliss, 2004).

1.5 Benefit of Safe Infrastructure

The importance of transport infrastructure for achieving economic development objectives in middle and low income countries is now widely recognized. Recent reports from the UN Millennium Project led by Professor Jeffrey Sachs; the OECD Development Assistance Committee, the UK’s Commission for Africa, and the UN Economic Commission for Africa have all recommended renewed attention to transport infrastructure. Functioning road infrastructure is also essential for delivery of vital services, including education and health services. The UK Department for International Development’s health strategy 'Working together for better health’, published in June 2007; recommends that: "key elements of an effective health system include essential infrastructure, such as hospitals, roads, and water systems...improved infrastructure such as roads and transport helps overcome practical barriers to accessing health facilities".

Road infrastructure has a central role in most national economic development strategies and accounts for a large proportion of expenditure by the multilateral development banks, which together have an annual portfolio of $4 billion for road construction and rehabilitation. It is therefore very important that safety design and management is a primary consideration in road construction and rehabilitation projects.

There is only short term economic value in building or rehabilitating a road without investing in safety. Aside from the direct economic and social costs of road crashes cited above, road traffic crashes are one of the leading causes of traffic congestion and reduced road capacity, with a recent official study finding that 25% of traffic congestion incidents in the US are caused by road crashes (Congressional Research Service, 2007).

Road engineering and effective road management can greatly reduce the frequency and severity of road traffic crashes, but poor engineering and poor management can contribute to crashes. The road network has an effect on crash risk because it determines how road users perceive their environment and provides instructions for road users, through signs, traffic controls, and road design, on what they should be doing. Many traffic management and road safety engineering measures work through their influence on human behavior.

Negative road engineering factors include those where a road defect directly triggers a crash, where some element of the road environment misleads a road user and thereby creates error, or where some feasible physical alteration to the road that would have made the crash less likely, or would have mitigated the consequences of a crash, has not been made.

Several studies quantified the effect of improved infrastructure on the number of fatalities and serious injuries. For example in the UK, a study by Burrough in 1991 concluded that one-third of the target reduction will be delivered by road safety engineering measures. A comparative study for the source of traffic fatality savings in the SUN country as described in the SUNflower report (Koornstra *et al*., 2002) concluded that vulnerable road users related measures have contributed to 29% to 38% of the reduction in fatalities in Sweden, Britain, and The Netherlands between 1980 and 2000 .

In the old language of the three 'E', it could be argued that Education and Enforcement will bring quickest results, followed by Engineering. However safety management capacity in low and middle-income countries is generally weak and it will take at least a decade of sustained action to strengthen it. This suggests that large scale 'mass action' infrastructure safety programs will provide the greatest opportunity to achieve quick results. Since 50% to 90% of all traffic related fatalities in low and middle-income countries are VRUs (pedestrians, cyclists, and motorcyclists), it is important to take into considerations this group in any road safety management system or national policy. Speed management and appropriate infrastructure for vulnerable road users may lead to quickest and best results in fatality reduction. The SUN country comparative study (Koornstra *et al.,* 2002), shows that improved road and speed management are expected to be the major source of casualty reduction in those countries. This is trivial in those countries where road user behavior is generally good and the standard of the fleet is high (Table 1-3).

Table 1-3: Approximate Distribution of Policy Areas Expected to Yield Future Casualty Savings

Measure	Netherlands	Sweden	UK
	%	%	%
Road infrastructure and appropriate speed limits	50	59	44
Vehicles	26	20	35
Behavior	24	15	16
Other	-	6	5
Total	100	100	100

Researchers based in Sweden (Stigson *et al.*, 2007) found that 70 per cent of fatal *injuries* were caused by the road alone or in combination with the vehicle and/or human being. In half of these cases, experts considered that the fatal outcome would have been avoided if improvements were made to the road. For the other half, both improvements made to the road, the vehicle and/or the human being were needed to prevent the fatal outcome.

1.6 Infrastructure Safety Management

Figure 1-8 from the European Project RIPCORD shows the three proactive and two reactive approaches for the Road Infrastructure Management. In Figure 1-9, the infrastructure safety management system is broken down by type of roads (new and existing roads).

Road safety impact assessment is a proactive prevention for new schemes, usually taken at a high level and in conjunction with other assessments. Road

Safety audit is also a proactive prevention for new schemes, using the experience of past crash patterns such as collisions with roadside objects to identify and correct shortcomings in new designs. Road safety inspection is a third proactive prevention for existing roads using detailed checklists.

Hazardous location management or black spot management is a reactive cure for existing roads where high risk spots are identified in terms of the recorded number of crashes. Network safety management is the second reactive cure, similar to black spot management approach but for road sections.

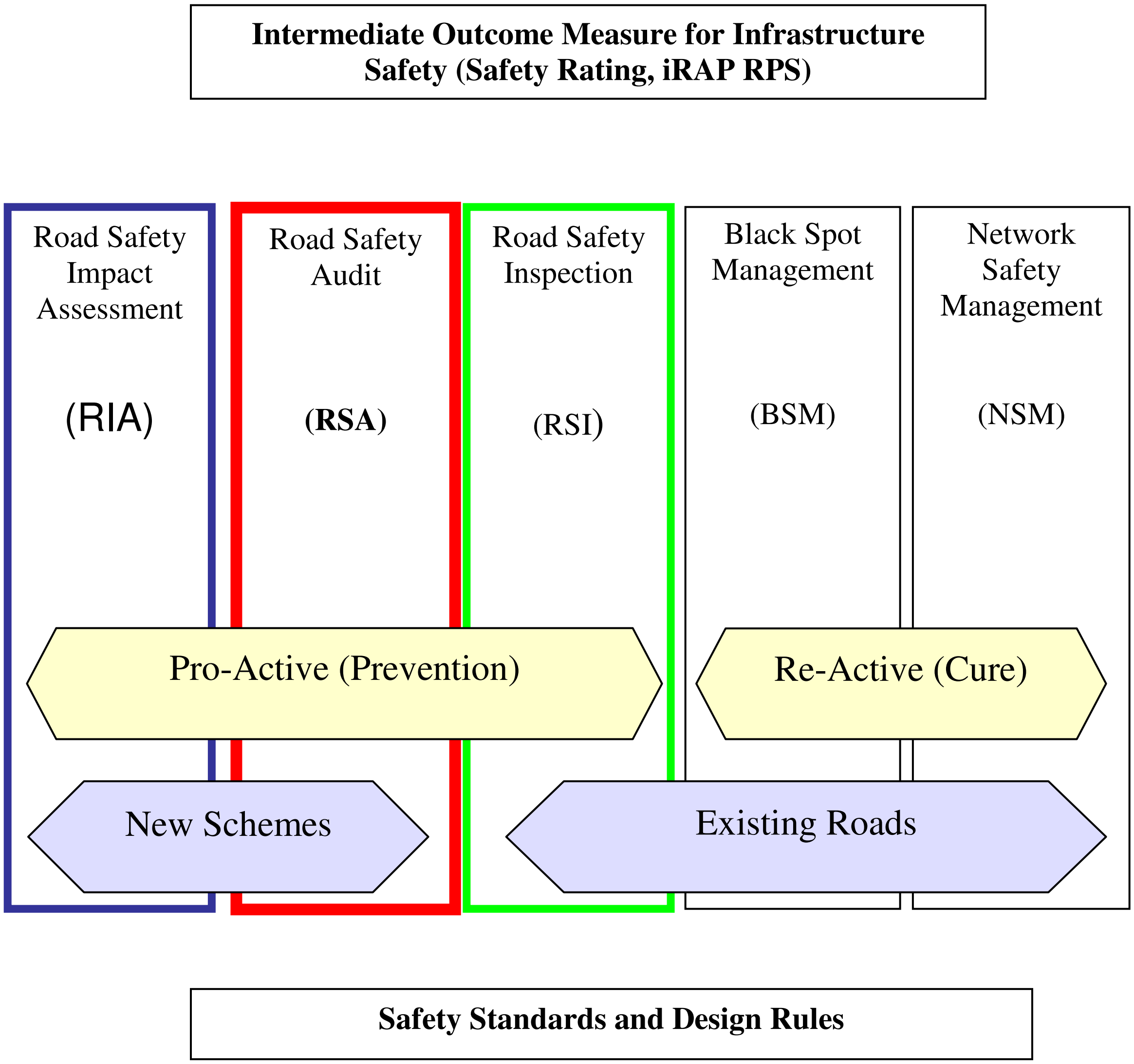


Figure 1-8: Road Infrastructure Safety Management I, European Project RIPCORD-ISEREST (with Amendment)

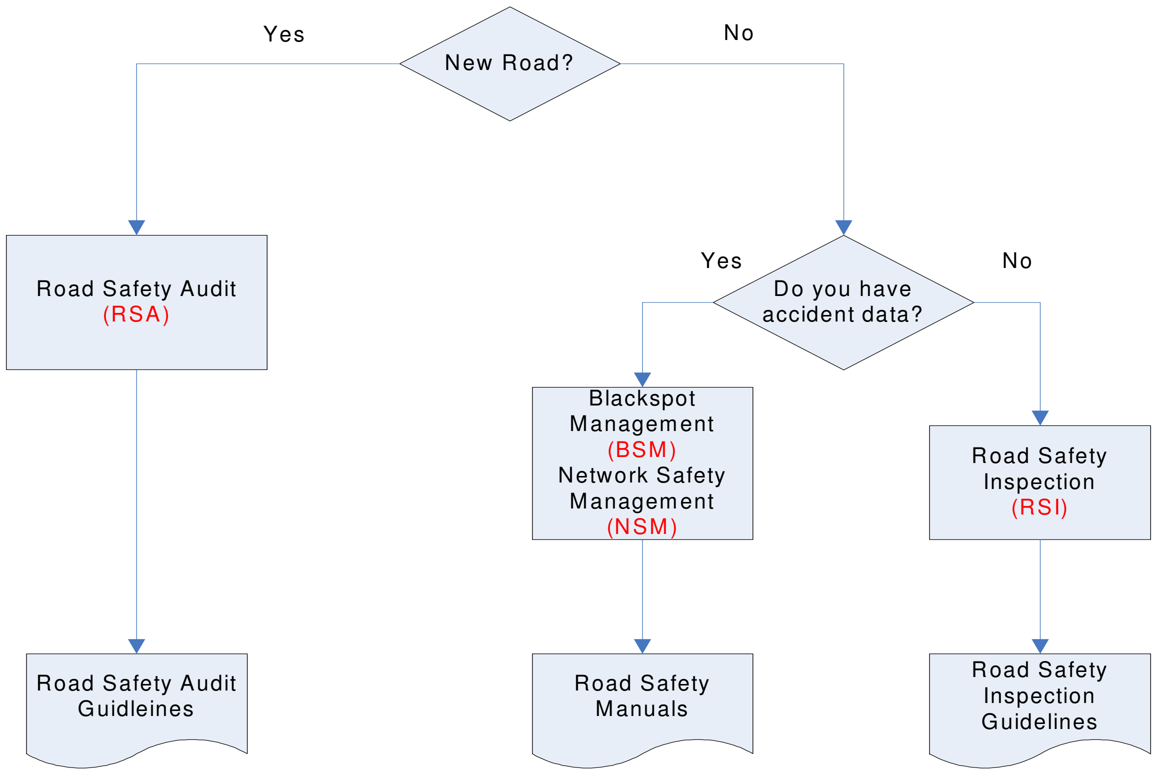


Figure 1-9: Road Infrastructure Safety Management II

1.7 Intermediate Outcome Measure for Infrastructure

The review presented in section 1.5 points to the fact that improving infrastructure and speed management will lead to most efficient results in reducing traffic related fatalities and serious injuries in low and middle-income countries, taking into consideration the VRUs problem in those countries. It has also been shown that advanced systems in road safety management require an intermediate outcome measure that can give an idea of the likely safety performance. Intermediate outcomes are sometimes referred to as safety performance indicators (SPIs), which are seen as any measurement that is casualty related to crashes or injuries and are used in order to indicate safety performance or understand the process that leads to casualties (Hakkert, 2007). They also provide the link between the casualties from road crashes and the measures to reduce them (ETSC, 2006).

None of the infrastructure safety management approaches presented in section 1.6 can be used as an intermediate outcome measure for infrastructure in low and middle-income countries. This is mainly because they either require detailed crash data that is not available for low and middle-income countries, or they do not meet the definition of intermediate outcome. It also cannot be used as an intermediate outcome measure because of the different road and traffic conditions in those countries, including the vulnerable road users' issue. Therefore, the question remains; what is an intermediate outcome measure for infrastructure that can be applicable in low and middle-income countries?

In the EU FP6 project SafetyNet (Hakkert, 2007), it was noted that, for the assessment of detailed road design, there is no direct SPIs in use at the moment. Two methods can be used to formulate indirect SPIs: The Road Protection Score (RPS) of EuroRAP and the Dutch Sustainable Safety Indicator (SSI). These methods score specific road design elements and can be used to formulate SPIs for road design. Both methods pay attention to homogeneity of the road traffic and forgiving road environment. The SSI has strong roots in the Dutch Sustainable vision; it therefore takes into account the predictability of the road environment and the function in the network of the distinguished sustainable safe road category.

1.7.1 The EuroRAP Road Protection Score (RPS)

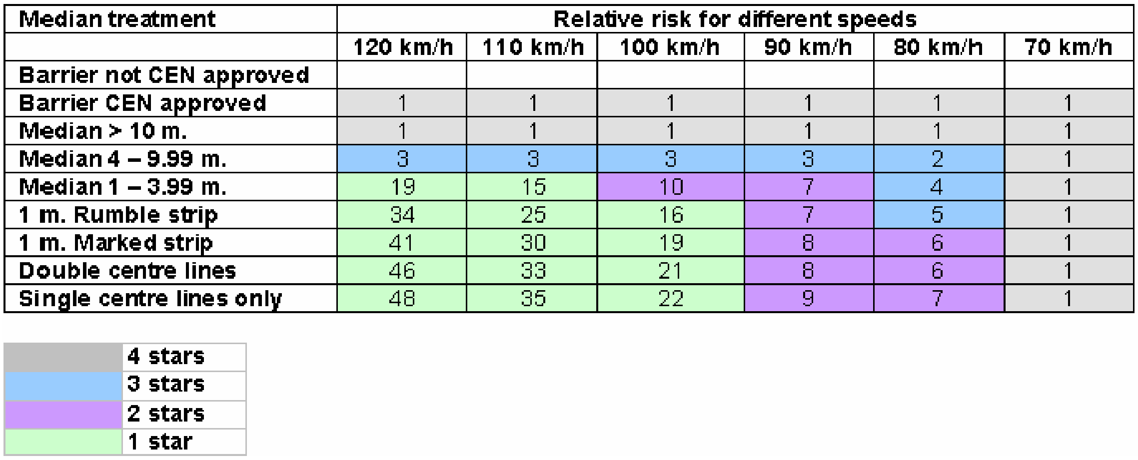
The European Road Assessment Program (EuroRAP) was designed as a complementary activity to the European New Car Assessment Program (EuroNCAP), developed in the 1990s. EuroNCAP involves crash tests of new cars and awards each vehicle with a star rating according to the protection given. According to EuroRAP (Lynam, 2003), a similar rating system for roads should help optimize the combined effect of road and vehicle safety. EuroRAP was therefore piloted to rate Europe's various roads for safety.

According to EuroRAP, four types of crashes contribute to about 80% of all fatal and serious crashes on major roads outside urban areas. The four types are single run-off the road crashes, head-on collisions, crashes at intersections, and crashes involving vulnerable road users (VRUs). The total percentage is common to many countries, but the distribution of the crash proportion between the four types differs according to the existing nature of the road network and traffic patterns in each country.

In addition to the so-called risk mapping, the EuroRAP Program contains a direct (visual) inspection of road quality. The aim of this survey is to produce a score for each route section that enables it to be compared with other sections. The main Road Protection Score (RPS) is based on separately scoring the protection provided in relation to three of the four main crash types (the VRU related crashes are excluded), and then combining their scores into an overall score of 1-4 stars. The combination of the component scores is weighted in proportion to their average occurrence across a range of European countries.

The RPS focuses on the road design and the standard of road-based safety features. “Protection” in this sense describes protection from injury when collisions do occur (secondary safety). The classes or values that are used for the scoring of each road characteristics are speed limit, median treatment, road side areas (cut and embankment, barriers), junctions, and intersections (type and access). The score for each crash component is based on a family of risk curves reflecting the speed limit for traffic on the road and the potential variation in road design relevant to crash type. As an example of those risk curves (20), Table 1-4 shows the relative risk of fatal or serious injury head-on crash by speed and median type.

Table 1-4: Assumed Relative Risk of Fatal or Serious Head-on Crashes by Speed and by Median Treatment. (Lynam *et al.*, 2003)



Median treatment	Relative risk for different speeds					
	120 km/h	110 km/h	100 km/h	90 km/h	80 km/h	70 km/h
Barrier not CEN approved						
Barrier CEN approved	1	1	1	1	1	1
Median > 10 m.	1	1	1	1	1	1
Median 4 – 9.99 m.	3	3	3	3	2	1
Median 1 – 3.99 m.	19	15	10	7	4	1
1 m. Rumble strip	34	25	16	7	5	1
1 m. Marked strip	41	30	19	8	6	1
Double centre lines	46	33	21	8	6	1
Single centre lines only	48	35	22	9	7	1

⬜	4 stars
🟦	3 stars
🟪	2 stars
🟩	1 star

The current EuroRAP Road Protection Score (RPS) does not take into account the Vulnerable Road Users (VRUs) related crashes or the design consistency characteristics of the road that affect the likelihood of crashes. Therefore there is a need to extend the current RPS to include Vulnerable Road Users and likelihood of fatal or serious crash occurrence.

1.7.2 Methodology to develop an RPS for Vulnerable Road Users

The approach to be used in extending the current Road Protection Score (RPS) to cover Vulnerable Road Users is to develop a risk matrix where the axes are the likelihood and the severity of Vulnerable Road Users related crashes.

The research will involve a review of the effect of speed and road design characteristics on the likelihood and the severity of Vulnerable Road Users related crashes. The study will concentrate on pedestrian crashes, emphasizing the effect of speed on the severity of pedestrian related crashes once they do occur.

1.8 Significance

This research describes and defines the first safety performance indicator for infrastructure safety to be used in low and middle-income countries. The model will be tested, and calibrated in several low and middle-income countries by the International Road Assessment Program (iRAP).

This research results in derivation of a pedestrian injury risk function based on the combination of crash data (PCDS) and a validated pedestrian simulation model.

This research evaluates the crashworthiness of an engineering countermeasure (physical steel fence) that is widely used in East Asia (China) to separate between the motorized vehicles and the bicyclists' lanes. Such evaluation will serve as an optimization tool for designers while setting up separators between vehicles and bicyclists.

Every engineering countermeasure shall be justified economically and for the first time this research sets up a methodology that is consistent worldwide to estimate the value of statistical life and serious injury in road safety.

The research will be used as a tool in the appraisal phase of the World Bank financed transport projects. The World Bank currently does not have at its disposal a systematic approach to ensure the safety of the roads that are parts of the Bank's transport portfolio (around $ 4 billion per year). The Bank also needs a tool for guiding the decision-making process to identify safety improvement needs and for developing a system-wide program of site-specific improvement projects.

Traditional Road Safety Audits take place as a small component in some transport projects and the World Bank is in need of having a systematic cost – effective approach that can be applied easily during the preparation phase of the transport projects and provides a political, policy, and targeting focus.

In other words, the World Bank and other development agencies lack a safety performance indicator that can be used and benchmarked throughout transport projects in low and middle-income countries. It is believed that such safety rating score can be used as an infrastructure safety performance indicator and this is proposed in the EU project SafetyNet because of the two main reasons:

- all road design elements are broadly accepted as relevant for road safety, and
- the method itself is worked out in detail and already in use in a lot of European countries

1.9 Contents of Chapters

Chapter 2 consists of a review of the literature with respect to current road safety tools used worldwide, accident modification factors for pedestrian and bicyclists accidents, injury risk functions for pedestrians, and simulation studies of pedestrian crashes.

In Chapter 3 crash likelihood risk curves for speed and road design affecting vulnerable road user's crashes will be developed. This will form the vertical axis of the risk matrix and in Chapter 4 injury severity risk curve will be developed for pedestrians using the NASS-PCDS database and MADYMO (TNO, 2005) simulations to validate this risk curve, which will complete the horizontal axis of the risk matrix.

Chapter 5 will combine likelihood and severity from previous chapters to formulate a total risk which is referred to as the road protection score (RPS) for pedestrians. Banding will be defined to star rate the roads based on the road protection score and a casualty prediction model will transform the unit less RPS to number of fatalities and serious injuries per kilometer of roads taking into consideration the traffic and pedestrian flow.

In Chapter 6, the crashworthiness of two designs of physical separators (fences) between cyclists and motor vehicle will be evaluated using finite element simulations.

In Chapter 7, values of life and serious injury in road crashes suitable for low and middle-income countries will be derived and an economic appraisal model to run cost benefit analysis will be developed and correlated with the casualty estimation model.

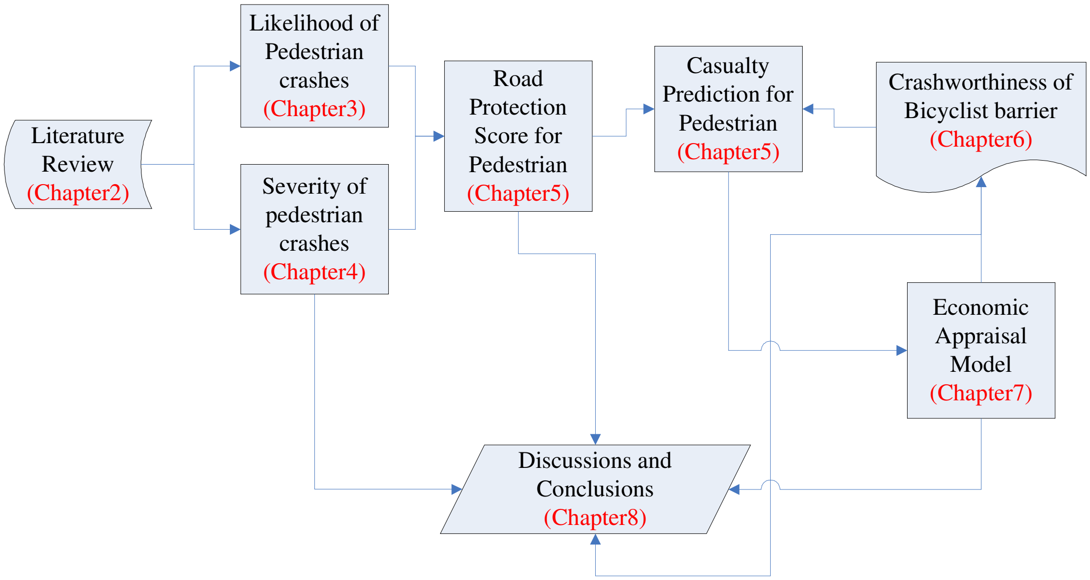


Figure 1-10: Contents of Chapters

CHAPTER 2

LITERATURE REVIEW

In order to develop a risk matrix for pedestrian crashes, this study reviewed previous literatures that discussed the risk of pedestrian crashes with respect to infrastructure design elements (per example number of lanes, crosswalk type), impact speed and other relevant predictors that form the risk matrix (both likelihood and severity) of pedestrian crashes. Likelihood axis will be referred to as accident modification factors and the severity axis as protection factors that are derived from risk functions.

2.1 Accident Modification Factors for Pedestrians/Cyclists

A 2001 study by McMahon *et al.* was conducted to identify the type of risks to pedestrians who are "walking along a roadway" and to quantify the relationship of such crash risks with roadway and neighborhood factors. Physical roadway features to be associated with a significantly higher likelihood of having a "walking along roadway" pedestrian crash included lack of a walk able area and the absence of sidewalk augmented by higher traffic volume and higher traffic speed limits. The likelihood of a site with a sidewalk or wide shoulder 9 of 4 feet or wider having a "walking along roadway" pedestrian crash was 88.2 percent lower than a site without a sidewalk or wide shoulder at the sites studied. Accident Modification Factors AMFs were not developed from the results.

Very few studies were found that have quantified the effects of sidewalks or walkways on pedestrian crashes or crash risk. This is likely due in part to the fact that pedestrian crashes are relatively rare at any given location and because of the difficulty of finding enough new sidewalks additions to conduct a proper before-after evaluation. Furthermore, installing sidewalks or walkways is more likely to reduce certain types of pedestrian crashes, such as where pedestrians are walking along roadways and are struck by a motor vehicle.

Researchers in Denmark have evaluated the effectiveness of Bicycle Lanes (BLs) as a bike safety measure. One study by Herrstedt *et al.* (1993) found a lower frequency of crashes resulting in injuries to cyclists on roadways that had a BL or bicycle path, compared with roadways that did not provide these facilities. Many of other studies indicate a safety benefit after installation of bicycle lanes. However, regression-to-mean may play a part in these studies; therefore the magnitude of safety effect is not known at this time.

2.2 Speed Related Risk Functions for Pedestrians

Ashton and Mackay (1979) developed a cumulative distribution function for impact speeds of 81 pedestrian fatal cases for Great Britain. His sample was normally distributed with a mean impact speed of 50 km/h and a standard deviation of 12 km/h (Figure 2-1). It was concluded that 5% of pedestrian fatalities occurred at impact speed below 30 km/h while 50% of the fatalities occurred below 50 km/h and 80% below 60 km/h. Ashton also noted that the change from predominantly survivable injuries to predominantly fatal injuries takes place between 50 km/h and 60km/h.

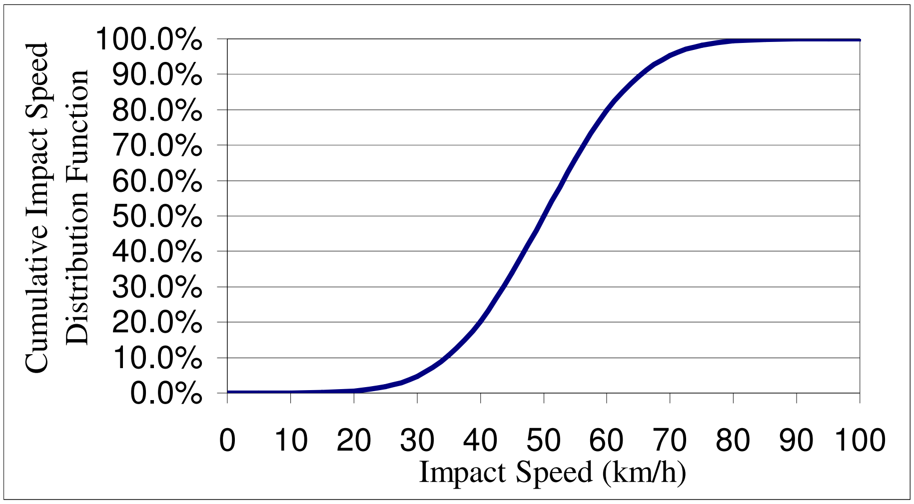


Figure 2-1: Cumulative Impact Speed Distribution of Fatal Pedestrians (Ashton, 1979)

This cumulative distribution function has been widely miss-interpreted and used as a risk function to predict the risk of pedestrian fatality at a certain speed. Peden *et al.* (2004) in the World Report on Road Traffic Injury Prevention used similar cumulative distribution function developed by Pasanen (1991) and conclude that a pedestrian have 50% risk of being fatal if impacted at speed of 45 km/h while the correct interpretation should be that 50% of the fatalities in the sample happened at impact speeds of 45 km/h or less.

In 1991, Pasanen also developed a theoretical risk curve relating the pedestrian fatality risk to the vehicle impact speed (Pasanen, 1991). This curve shows that there is less than a 10% risk that a pedestrian struck by a vehicle traveling at 30 km/h dies, and a 50% risk when struck at 53 km/h, and that nearly 100% risk of death at 80 km/h. The collision speed of 50 km/h increases the risk of a pedestrian death almost eight-fold compared to a speed of 30 km/h. There is almost no pedestrian fatality in crashes with speeds below 20 km/h.

McLean *et al*., (1994) showed a direct correlation between reducing the risk of pedestrian fatality and vehicle traveling speed reduction. In his study, it was estimated that a uniform reduction of 10km/h in traveling speeds in 60km/h speed limit zones would reduce the fatal pedestrian cases by 48 percent, including the elimination of the collision in 22 percent of all cases. It was also concluded that the probability of death if a pedestrian is struck at an impact speed of 60 km/h is 100%; this compares to 84% if struck at 50 km/h and 26% if struck at 40 km/h.

The European Transport Safety Council (1995) reported that only 5% of pedestrians died when struck by a vehicle traveling at 32 km/h; however, the proportion of fatalities increased to 45% at 48 km/h and to 85 percent at 64 km/h.

Davis *et al*., (2002) modeled the relationship between impact speed and pedestrian injury risk by age group and injury severity level using the same data as Ashton The impact speed at which the chance of fatal injury is 50% occurs between 70 and 75 km/h, as opposed to 53 km/h (Pasanen and Salmivaara, 1993) or 45 km/h (McLean *et al.,* 1997).

Cuadrado *et al*. (2008) showed a non-continuous relationship between pedestrian serious injury (MAIS3+) risk and impact speed using the Pedestrian Crash Data System (PCDS) that requires further statistical analysis (Figure 2-2). Two plateaus are observed in the analysis of the serious injury risk; the data shows a relatively constant risk between 16-30 km/h and between 38-48 km/h. This has to be closely investigated through more in-depth analysis for the cases within those two intervals and through simulations to further study the dynamics as well as the biomechanics of the pedestrian's injuries. This curve is consistent with previous studies in showing a sharp increase in pedestrian risk between 30 and 50 km/h.

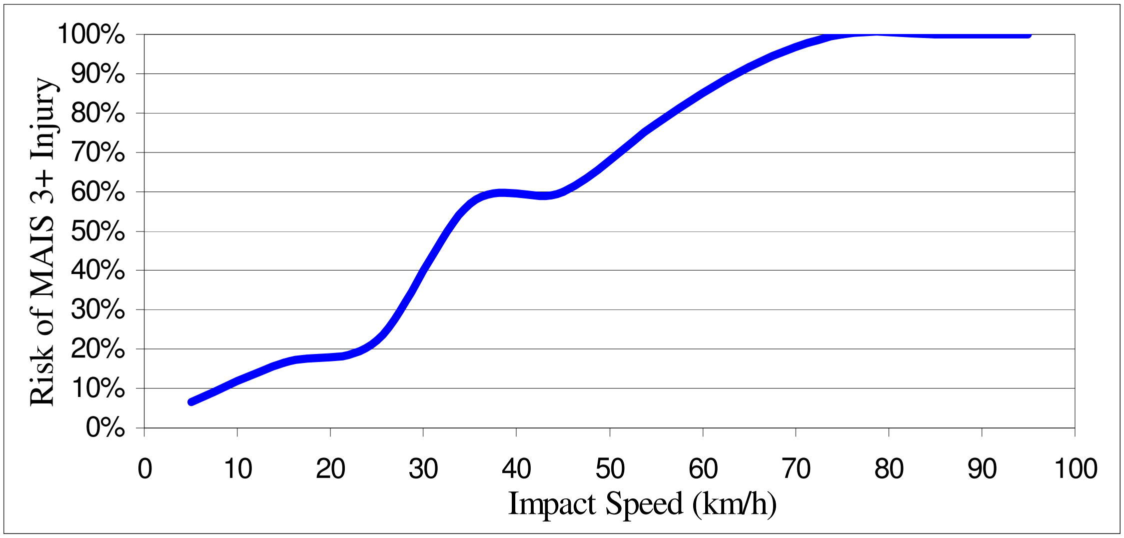


Figure 2-2: Risk of MAIS3+ Injury (PCDS Database)

As described in this review of the literature, several studies show different risk of pedestrian fatality with respect to impact speed. Only studies by Davis *et al.* (2002) and that of Cuadrado *et al.* (2007) have developed a risk function for pedestrian serious injuries. Therefore, there is a need to develop a pedestrian serious injury risk function as well as a new fatal risk function using the more updated and accurate data of the PCDS database.

2.3 Pedestrian Collisions Simulations

Yoshida *et al.* (1998) developed a computer system and human body model to simulate road crashes involving pedestrians. He used an ellipsoid dummy model that consists of 15 ellipsoids. Two different vehicle models were available in his system. One was conventional ellipsoids and planes model and the other one was

Finite Element model that represents the actual front-end structure of a vehicle. The correlation between simulation results and PNHS test data was studied.

Coley *et al.* (2001) in his study focuses on modeling a real-world accident to determine how such a methodology can be used to further validate an improve current pedestrian human models. A scaled version of the TNO 5th percentile female pedestrian has been validated and applied to reconstruct a fatal accident using a detailed vehicle model. Further impact scenarios have been explored to allow the 'injury variation' based on stiffness and pedestrian position.

Glatin *et al.* (2002) used an FE/MBS vehicle model to simulate pedestrian crashes. Due to lack of access to real world pedestrian crash data to validate pedestrian to vehicle impact simulation, it was decided in this study to evaluate the response of each individual component of the pedestrian vehicle system. The pedestrian model used was the multibody MADYMO pedestrian human model developed by TNO. The validity of the pedestrian human body model was evaluated using published results from impact tests with cadavers. A visual comparison of the resultant kinematics between the human cadaver test and the computer simulation showed that the overall kinematics of the pedestrian is in good agreement with the recorded high-speed film from impact tests. Following of the validation of the FE vehicle model and the application of a pedestrian human body model, a method of validating the entire pedestrian to vehicle impact was investigated. The authors used the Design of Experiment (DoE) techniques to analyze the results from real world pedestrian to vehicle accident simulations.

Ishikawa *et al.* (1998) developed a new mathematical multibody system model to simulate the pedestrian in road accidents with cars. The pedestrian model was created to be used with the crash victim simulation (CVS) computer program. The model consists of fifteen segments connected with fourteen joints. The model was validated against cadaver experiments. The model response to the following parameters was studied: impact speed, bumper height, and bumper compliance. The responses from the model in various impact configurations, such as overall pedestrian behavior, head resultant velocity, acceleration of the segments and so on, were validated.

Anderson *et al.* (2002) performed reconstructions of 10 pedestrian crash using numerical and laboratory methods. The reconstructed crashes were selected from among 80 pedestrian crashes collected by the Australian Commonwealth Department of Transport and Regional Services. A MADYMO pedestrian model was used to simulate the crashes, with the average male model scaled to match the pedestrian's size. The vehicle model was approximated with planes and ellipsoids.

Stammen *et al.* (2001) reconstructed several PCDS cases at the NHTSA Vehicle Research and Test Center; also computer simulations have been conducted. A pedestrian accident case was selected from the PCDS database for reconstruction with computer simulation and testing. The vehicle used in the reconstruction was a 1996 Ford Taurus Sedan. The recorded speed at impact was 27 km/h, the pedestrian was 48-yr old male (height 178 cm, weight 82 kg). They were able to replicate an actual case and the similarity of the results for the testing and simulation encourages the use of these techniques to make a connection between injuries occurred in an accident and acceleration/force measurement in reconstructions.

2.4 Value of Statistical Life in Road Safety

There are official values of statistical life (VSL) in various countries that are recommended for policy support and assessment. De Blaej *et al.* (2004) made an inventory of the most up to date VSL values in 7 countries within the framework of the EU ROSEBUD project. These values vary between 1.4 million and 2.6 million (price level 2000).

Within the framework of the EU UNITE project, the EC developed a proposal for European core data, including a standard VSL. A standard VOSL of € 1.5 million (price level 1998) was proposed in the Valuation Conventions for UNITE (Nellthorp *et al.,* 2001). This value is differentiated per country, taking difference in purchasing power into account. Per example, the UNITE value for the Netherlands was € 1.7 million.

In valuing reductions in premature fatalities, the US DOT uses a value of $ 3.5 million per statistical life as of January 2004. The most recent study relating to the cost of crashes published by NHTSA (Blincoe *et al.,* 2002) as well as the most current DOT guidance on valuing fatalities (USDOT Memorandum, 2002), indicate a value consistent with $ 3.5 million. This value is an update of the 2000 value of $ 3 million.

Notwithstanding the above, there is an abundant empirical literature on the subject of VOSL in road safety. However the magnitude of VSL estimates reported in the literature is vastly different , going all the way from less than 400,000 to 30 million in 1996 U.S Dollar (Cohen , 1980; Persson , 1991).

2.5 Review of Relevant Road Safety Tools

In order to develop a sustainable infrastructure safety performance indicator, it was necessary to review all available tools that serve as network screening or accident prediction models that are being currently used by transport agencies or research firms for road safety management throughout the world.

The *Interactive Highway Safety Design Model* **(IHSDM)** is a suite of software analysis tools for evaluating safety and operational effects of geometric design decisions on two-lane rural highways. IHSDM is a decision-support tool. It checks existing or proposed two-lane rural highway designs against relevant design policy values and provides estimates of a design’s expected safety and operational performance. IHSDM results support decision making in the highway design process. Intended users include highway project managers, designers, and traffic and safety reviewers in state and local highway agencies and engineering consulting firms (http://www.tfhrc.gov/safety/ihsdm/ihsdm.htm).

SafetyAnalyst is envisioned as a set of software tools used by state and local highway agencies for highway safety management. SafetyAnalyst will be used by highway agencies to improve their programming of site-specific highway safety improvements. SafetyAnalyst will incorporate state-of-the-art safety management approaches into computerized analytical tools for guiding the decision-making process to identify safety improvement needs and develop a system wide program of site-specific improvement projects. SafetyAnalyst will have a strong basis in cost-effectiveness analysis. Thus, SafetyAnalyst will have an important role in ensuring that highway agencies get the greatest possible safety benefit from each dollar spent in the name of safety (http://www.safetyanalyst.org).

Similar to the Highway Capacity Manual, the *Highway Safety Manual* **(HSM)** will serve as a useful tool for practitioners in helping them make decisions. The purpose of the HSM is to provide the best factual information and tools in a useful and widely accepted form and to facilitate road investment and operation decisions based upon explicit consideration of their safety consequences. This manual will greatly strengthen the role of safety in road planning, design, maintenance, construction, and operations decision making.

(http://www.highwaysafetymanual.org)

The *Highway Safety Information System* **(HSIS)** is a multistate database that contains crash, and roadway inventory, as well as traffic volume data for a select group of states. The HSIS can be used to analyze a large number of safety problems, ranging from the more basic "problem identification" issues to identifying the size and extent of a safety problem to modeling efforts that attempt to predict future accidents from roadway characteristics and traffic factors. (http://www.hsisinfo.org)

The Pedestrian and Bicycle Crash Analysis Tool **(PBCAT)** is a crash typing software product intended to assist state and local pedestrian/bicycle coordinators, planners, and engineers with improving walking and bicycling safety through the development and analysis of a database containing details associated with crashes between motor vehicles and pedestrians or bicyclists. One of these details is *crash type*, which describes the pre-crash actions of the involved parties. After developing a database of crash information, PBCAT users can analyze the data, produce reports, and select countermeasures to address the problems identified by the software (http://www.walkinginfo.org/facts/pbcat/index.cfm).

EuroRAP is a sister program to *EuroNCAP*, the independent crash test program that star rates new cars for the crash protection they provide to passengers and pedestrians. EuroNCAP demonstrates that well-designed crash protection can make family cars safer. Similarly, EuroRAP is beginning to show how roads can be made safer, so that the car and road work together to protect life. EuroRAP aims to provide independent, consistent safety ratings of roads across borders. Thousands of road stretches across Europe have already been assessed and the methods used are already being applied in Australia through AusRAP and piloted in the USA through usRAP. EuroRAP provides three protocols that can be applied to any country: Risk Mapping, Performance Tracking, and Star Rating (http://www.eurorap.org).

The PIARC Road Safety Manual **(RSM)** compiles the experience from different countries as it presents state-of-the-art information and guidance for the design and operation of road infrastructure in order to increase road safety. Part 1 is an introduction to Road Safety and gives an overview of the problem. It is designed to help transportation professionals better understand the potential, as well as the limitations, of available solutions. Part 2 describes the complete road safety improvement process, from data collection to the impact of solutions that are available for implementation. Part 3 covers the main technical characteristics of the road infrastructure and the relationship to human factors. Part 4 reviews different aspects of technical studies of safety analysis (http://www.piarc.org).

SafetyNet is an Integrated Project funded by DG-TREN of the European Commission. The objective of the project is to build the framework of a European Road Safety Observatory, which will be the primary focus for road safety data and knowledge, as specified in the Road Safety Action Plan 2003. The Observatory will support all aspects of road and vehicle safety policy development at European and national levels. It will make new proposals for common European approaches in several areas, including exposure data and Safety Performance Indicators. One of the areas that have been identified for the development of a safety performance indicator is the Road. The EuroRAP Road Protection Score was adopted and the SPI for roads but it was noted that Vulnerable Road Users are not yet implemented in the RPS and this needs more work (http://www.erso.eu/safetynet/content/safetynet.htm).

The Road Network Safety Assessment **(RNSA)** has been developed in the Australian State of Queensland. This model differs from the AusRAP RPS approach and covers all roads across the network (sealed and unsealed, intersections and road section). The aim of the RNSA methodology is to provide road authorities across the state with a sound basis to pro-actively identify road safety issues across their network and ultimately develop a well prioritized works program to address the concerns identified. The Network Risk Score is based on the research behind the *Road Safety Risk Manager* and includes components related to the road type (urban vs. rural, mid-block vs. intersection) and road elements impacting crash likelihood (e.g. horizontal alignment, lane width, shoulder width, surface conditions etc.) and road elements impacting severity (speed, roadside environment, type of crash). The location and assessment of the road network can be undertaken by either driving the road network or through the use of geo-referenced digital video or similar imaging of the road network (http://www.arrb.com.au).

From this literature review, it is clear that none of these tools except the Pedestrian and Bicycle Crash Analysis Tool addresses the safety of vulnerable roads users. Moreover, some of these tools require crash data.

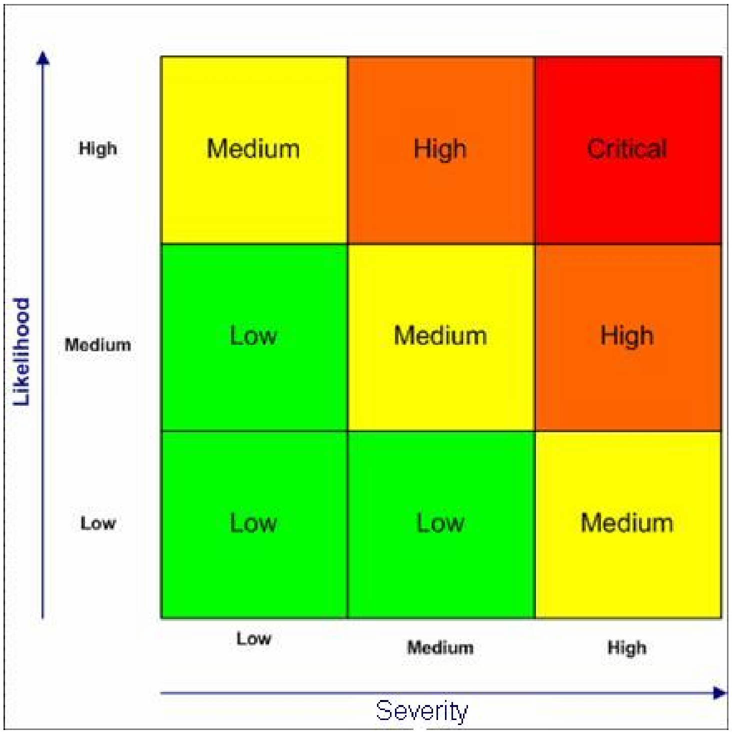
The AusRAP RPS methodology is the one to be adopted by iRAP in developing the safety rating system for developing countries. That method takes into consideration the road features that affect both the likelihood and the severity of the crash. Therefore, there is a need for a literature review that categorizes these features for vulnerable road users and for the identification of risk factors for each item to develop the safety rating system for VRUs (http://www.ausrap.org).

CHAPTER 3

THE LIKELIHOOD OF PEDESTRIAN CRASHES

3.1 Introduction

Risk is the composite of the predicted likelihood and severity of the outcome or effect (harm) of the hazard in the worst credible system state (Figure 3.1). In order to assess the risk of a crash or incident occurring, likelihood and severity are first determined.



Likelihood	Low	Medium	High
High	Medium	High	Critical
Medium	Low	Medium	High
Low	Low	Low	Medium

Figure 3-1: Predictive Risk Matrix

This risk approach will be applied for pedestrian crashes. Speed, sidewalk provisions, and side friction are the main factors that affect the likelihood of a pedestrian being involved in a fatal or serious injury crash while walking along the road. Speed, the number of lanes used by through traffic, median type, pedestrian crossing facilities, and the quality of crossing are the main factors to affect the likelihood of a pedestrian being involved in a fatal or serious injury crash while crossing a road.

The likelihood of a fatal or serious injury crash that involves a pedestrian forms the vertical axis of the risk matrix of pedestrian crashes..

The likelihood factors for each infrastructure aspect represents the relative risk of a pedestrian being involved in a fatal or serious injury crash, with everything else being equal, based on the safety embedded in that infrastructure factor (e.g. number of lanes, crossing type, etc.). This does not include any behavior factor, such as jaywalking, while traffic signals for pedestrians are present. A likelihood factor of 1 will be assigned to attributes for which it is almost inconceivable that the event of a pedestrian fatal crash will occur. A likelihood factor of greater than 1 will be assigned for other attributes for which the event may occur at different frequency level. The resultant likelihood value will be the product of all likelihood factors for each item (per example speed, number of lanes) that contribute to the occurrence of a pedestrian fatal crash.

3.2 Likelihood of a Pedestrian Crash While Walking Along the Road

Likelihood Factor for walking along the road = Speed - likelihood

x Sidewalk provision – likelihood

x Side friction (3.1)

A baseline attribute for each infrastructure item will be chosen and assigned a risk of 1 to which other attributes are compared and assigned a relative risk number. For example, a risk of 1 will be assigned for speeds equal to 120 km/h while speeds less than 120 km/h will be assigned a risk less than 1.

3.2.1 Speed Likelihood Factors

The relationship between speed limit and number of pedestrian crashes is assumed to be linear (Lynam, 2007). It is assumed that 1 is the risk of crash occurrence on roads with a speed limit of 120 km/h, the risk of crash occurrence on roads with speed limit equal to x will be x/120. Table 3-1 shows the effect of speed of the likelihood of pedestrian crash.

Table 3-1: Effect of Speed Limit on the Likelihood of Pedestrian Crashes

Speed Limit	Likelihood Factor
30 km/h	0.25
40 km/h	0.33
50 km/h	0.42
60 km/h	0.50
70 km/h	0.58
80 km/h	0.67
90 km/h	0.75
100 km/h	0.83
110 km/h	0.92
120 km/h	1.00

3.2.2 Sidewalk Provision Likelihood Factors

Sidewalk provision can be footpaths that are separated from the traffic by a physical barrier, a non-physical separation, or adjacent to traffic. Some roads have paved shoulders with variable width, while others do not have any provisions for pedestrians to use while walking along the road. Lynam (2007) quantified the effect of several sidewalk provisions on the likelihood of pedestrian crashes and represented in Table 3-2.

Table 3-2: Effect of Sidewalk Provisions on the Likelihood of Pedestrian Crashes

Sidewalk Provision	Likelihood Factor
Footpath with physical barrier	1.0
Footpath with non-physical separation > 3m	1.0
Footpath with non-physical separation >1m	1.1
Footpath adjacent to traffic	1.2
Paved Shoulder > 1 m	1.4
Total shoulder > 1m	2.0
None	4.0

3.2.3 Side Friction Likelihood Factors

Side friction concerns the extent to which activities along the side of the road interact with through traffic on the road, increasing risk of impact with people or cars involved in the roadside activity or impact between those traveling along the road when they change their position to avoid roadside activity. Side friction can also occur where several buses or taxis stop to service roadside activities.

A low side friction means there is little interaction between roadside activities and through traffic, either through low activity levels or planned provision, such as service roads running parallel to the main road. A medium side friction is recorded where activities or parking on one side of the road spill out onto the road. A high side friction means the presence of activities or parking on both sides of the road that spill out onto the road. Table 3-3 represents the effect of side friction on the likelihood of pedestrian crashes as derived by Lynam (2007).

Table 3-3: Effect of Side Friction on the Likelihood of Pedestrian Crashes

Side Friction	Likelihood Factor
Low	1.0
Medium	1.1
High	1.2

3.3 Likelihood of a Pedestrian Crash While Crossing the Road

Likelihood Factor for crossing the road = Speed - likelihood

x Number of lanes for use by through traffic

x Median type - likelihood

x Pedestrian crossing facilities - likelihood

x Quality of crossing (3.2)

The effect of speed on the likelihood of pedestrian crash while crossing the road is assumed to be the same as walking along the road, therefore the table 3.1 will be used for speed likelihood factor of a pedestrian crash while crossing the road.

3.3.1 Number of Lanes Likelihood Factors

The number of lanes for use by through traffic is well known to affect the likelihood of pedestrian crashes while crossing the road. The more lanes a pedestrian has to cross, the higher the risk that he will be involved in a crash. Table 3-4 represents the effect of number of lanes on the likelihood of pedestrian crashes.

Table 3-4: Effect of Number of Lanes on the Likelihood of Pedestrian Crashes

Number of Lanes	Likelihood Factor
One	1.0
Two	1.5
Three	2.5
Four or more	4.0

3.3.2 Median Type Likelihood Factors

Table 3-5: Effect of Median Type on the Likelihood of Pedestrian Crashes

Median Type	Likelihood Factor
Barrier	1.0
Physical Median Width > 20 m	1.0
Physical Median Width 10-20 m	1.0
Physical Median Width 5-10 m	1.0
Physical Median Width 1-5 m	1.0
Physical median Width up to 1 m	1.5
Rumble Strip	1.6
Central Hatching	1.8
Continuous Central Turning Lane	2.0
Center Line Only	2.0

3.3.3 Pedestrian Crossing Facilities Likelihood Factors

Zegeer *et al.* (2002) found that the presence of a raised median or crossing island (refuge) was associated with a significantly lower rate of pedestrian crashes on multi-lane roads. Specifically, comparing urban or semi urban multi-lane roads with annual daily traffic (ADT) of 15,000 or more vehicles per day and marked crosswalks, the pedestrian crash rate was 0.74 with a raised median, compared to 1.37 for sites without a raised median. Thus, having a raised median was associated with 46% reduction in pedestrian crashes, compared to sites without a raised median. These results were used to develop an accident modification factor (AMF) of 0.54.

For sites at unmarked crosswalks locations, the pedestrian crash rate was 0.17 with a raised median compared to 0.28 for sites without a raised median. Thus, having a raised median at unmarked crosswalks was associated with 39% reduction in pedestrian crash rate, compared to sites without a raised median. These results were used to develop an AMF of 0.60 for raised median at unmarked crosswalks. These AMFs developed by Zegeer *et al.* (2002) were normalized to assign a value of 1 for grade separated facility or signalized intersection with refuge and other crossing facilities were scaled accordingly, that normalization results in likelihood factors for each pedestrian crossing facility (See Table 3-6)

Table 3-6: Effect of Pedestrian Crossing Facilities on the Likelihood of Pedestrian Crashes

Pedestrian Crossing Facilities	AMFs	Likelihood Factor
Grade Separated Facility	-	1.0
Signalized with Refuge	0.125	1.0
Signalized without Refuge	0.28	2.0
Unsignalised Marked with Refuge	0.28	2.0
Unsignalised Marked without Refuge	0.5	4.0
Refuge Only	0.6	4.5
No Facility	1	8.0

3.3.4 Quality of Pedestrian Crossing Facilities Likelihood Factors

Table 3-7: Effect of Quality of Crossing Facilities on the Likelihood of Pedestrian Crash

Quality of Crossing	Likelihood Factor
Adequate	1.0
Poor	1.2

3.4 Example of Likelihood Factors

An ideal road design for pedestrian safety is a 2 lane road, with a speed limit of 30 km/h with a sidewalk that is separated from the main road by a barrier with signalized intersection with refuge and a wide median. That road has likelihood factors of 0.25 for both crashes along the road and while crossing.

A random road design is illustrated in Table 3-8.

Table 3-8: Example of Attributes of a Random Road

Attribute	Value	Likelihood Factor
Speed Limit	60 km/h	0.5
Number of Lanes	2	1.5
Sidewalk Provision	Paved Shoulder > 1 m	1.4
Median Type	Physical Median Width 1-5 m	1.0
Crossing Facilities	Unsignalised Marked without Refuge	4.0
Quality of Crossing	Poor	1.2
Side Friction	Low	1.0

The likelihood factor of pedestrian crash while walking along this road is:

0.5*1.4*1.0 = 0.7.

This represents 2.8 times the likelihood on the ideal road design.

The likelihood factor of pedestrian crash while crossing this road is:

0.5*1.5*1.0*4.0*1.2= 3.6.

This represents 14.4 times the likelihood on the ideal road design.

3.5 Summary

The likelihood factors developed in this chapter will form the vertical axis of the risk matrix as described in Figure 3-1. The following chapter will develop the severity factors which will form the horizontal axis of the risk matrix. The product of both axes will be the 'risk' or what is referred to later as the Road Protection and Prevention Score (RPPS). The higher the RPPS is, the higher the 'risk' of a pedestrian being involved in a fatal crash is.

CHAPTER 4

THE SEVERITY OF PEDESTRIAN CRASHES

4.1 Introduction

In the previous chapter, the likelihood of a pedestrian being involved in a fatal crash was developed based on speed and relevant infrastructure characteristics. The severity component of the risk matrix will be developed in this chapter focusing on speed as the primary predictor of injury severity outcome for pedestrians involved in crashes. Sidewalk provision and pedestrian crossing facilities also play a role in the protection of pedestrians in a crash. While these two features affect the likelihood of a pedestrian fatal or serious injury crash, they still have little effect on the severity of the outcome. This is mainly because of the impact these facilities have on speed. For example, the impact speed at an unsignalised and unmarked crossing facility may be more than the one at a signalized intersection with refuge.

The severity axis of the risk matrix (referred to as protection factors) represents the risk of a pedestrian being fatal once involved in a crash. Therefore, the ultimate goal is to develop fatality factors that represent the relative risk of a pedestrian fatality compared to the 100% risk (protection factor of 1) with speed and other infrastructure attributes being the predictors.

In order to develop a pedestrian fatal risk function, there is a need to analyze an in-depth pedestrian crash database where information about impact speed and the injury severity are collected.

The 1994 – 1998 Pedestrian Crash Data Study (PCDS) conducted by the National Automotive Sampling System (NASS) will be used to develop an injury risk function for pedestrians, which will be the contribution of speed to severity outcome for pedestrians if involved in a crash. MADYMO simulations will be used to validate and explain the risk functions obtained from the PCDS data analysis.

4.2 Development of Pedestrian Injury Risk Functions Using NASS-PCDS

4.2.1 Description of the NASS-PCDS Database

The Pedestrian Crash Data Study (PCDS) provides detailed information to analyze different parameters (e.g. impact speed, age, vehicle type) contributing to the probability of fatality or serious injury in pedestrian crashes. While the relationship between vehicle speed and probability of fatal injury developed by Ashton and MacKay (1979) and Pasanen (1991) is useful, a validation exercise using the PCDS data is important, given the more defined and detailed nature of this data. Furthermore, since the previous studies, there have been changes in the vehicle type mix (car/truck) and in the shape and stiffness of the front of vehicles. Therefore, the study will focus on developing a relationship between sustained injuries by a pedestrian using the Maximum Abbreviated Injury Scale (MAIS) and impact speed.

The Pedestrian Crash Data System (PCDS) covers data from 1994 to 1998. Over this time, the PCDS includes detailed investigation of 552 cases involving pedestrians that were struck by a late model year vehicle. Each case contains photographs and videos of the accident scene as well as 144 variables that were recorded during the investigation including the maximum abbreviated injury-scale (MAIS) and the vehicle impact speed. Of particular importance is that the PCDS is the only U.S. pedestrian crash database in which the impact speed has been determined through accident reconstruction. This is the reason for its use in this study.

The availability of information on the following variables was deemed as necessary for a case to be considered in this study: gender, age, vehicle type, speed limit, and the accuracy of impact speed estimate All collected data were filtered through the use of the statistical program SAS to eliminate cases that did not contain all of the necessary information. After the filtering process, 412 cases met the requirements and were used in this research.

Figure 4-1 shows the distribution the number of PCDS cases by age and gender of the pedestrian. Although the number of cases for most groups is relatively small, this analysis may be pointing to several social factors that might be of interest in future studies. In particular, there are twice as many cases of males between the ages of 0-5 and the significant difference between the number of males and female for the age range of 26-35. These particular differences may be rooted in particular gender dependent social behaviors.

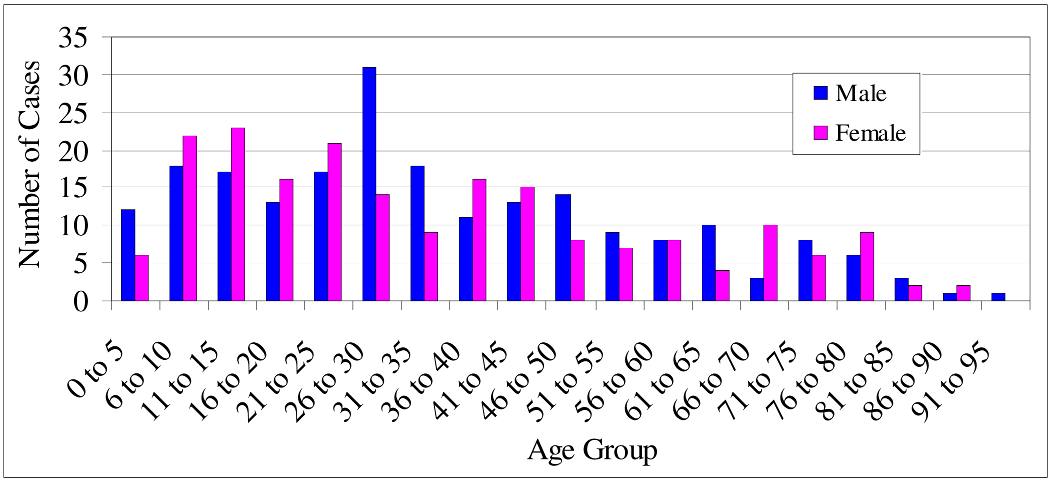


Figure 4-1: Number of PCDS Cases by Gender and Age Group.

The PCDS database is more suitable for serious injury rather than fatal injury risk analysis due to the small number of cases of pedestrian being fatally injured. Only 49 out of the 412 pedestrians were fatally injured, for this reason serious injury risk functions will be derived by different statistical methods but the results at the end will be translated into data injury risk function to form the protection factors or the severity axis in the risk matrix.

To examine the validity of the pedestrian sample used in this study, a comparison is performed on the breakdown of this sample by age, gender, vehicle type, speed limit, and area type with pedestrian fatal data as reported for same years (1994-1998) in the Fatality Analysis Reporting System (FARS).

Age distribution is similar for both databases, but FARS data contains more elderly people (13.2% vs. 5.8%) and a slight difference exists in the vehicle type distribution. Around 67% of the vehicles in PCDS are passenger cars, versus 54 % in FARS; therefore there are more Light Trucks in FARS compared to PCDS (See Table 4-1). The PCDS sample reflects the U.S. vehicle mix as LTVs comprise approximately one third of the entire Unites States vehicle fleet. The major difference between PCDS and FARS databases exists in area type; the majority of PCDS cases were collected from urban areas where the speed limit is less than 50 km/h and PCDS was designed to be a clinical study and was not intended to be a national sample of pedestrian crashes.

Within the automotive safety research, an MAIS value of 3 or greater will be considered 'serious' and MAIS values less than 3 will be considered 'minor'.

Table 4-1: Comparison between PCDS and FARS Databases

Age category	PCDS	FARS
< 5	4.4%	3.6%
5-10	9.7%	4.7%
11-15	9.7%	4.7%
16-20	7.1%	5.4%
21-24	9.2%	5.1%
25-34	17.5%	14.3%
35-44	13.4%	17.2%
45-54	9.2%	12.5%
55-64	7.3%	9.1%
65-74	6.6%	9.3%
75+	5.8%	13.2%
Vehicle Type	PCDS	FARS
Passenger Car	67.7%	53.9%
Light Truck Vehicles	33.3%	41.1%

Figure 4-2 shows the relationship between impact speed and injury severity for the overall population. As expected, the probability of sustaining a serious injury (AIS3+) increases as the impact speed increases. Over 80% of pedestrians struck at 20 km/h experienced minor injuries while 60% of them experienced major injuries at 50 km/h. Almost all pedestrians sustain a serious injury for impact speedshigherthan60km/h.

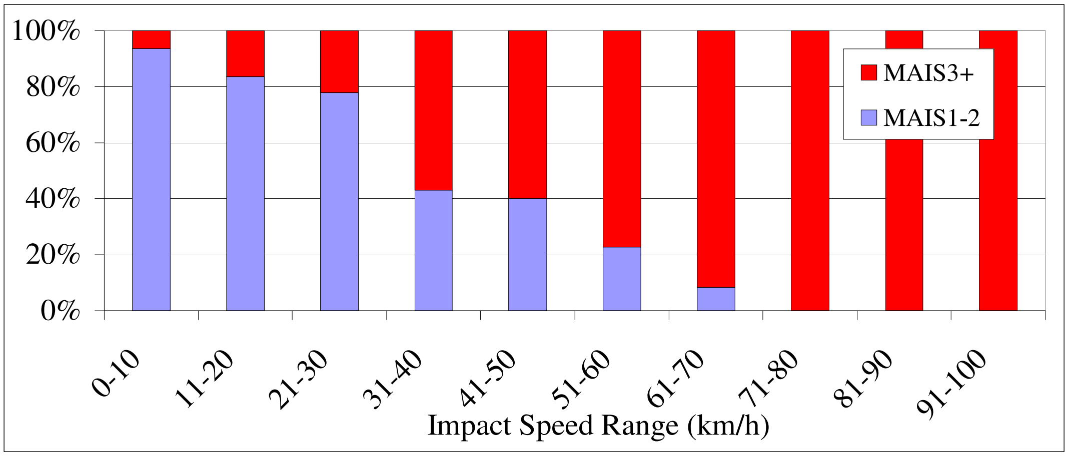


Figure 4-2: Proportion of Minor and Serious Injuries by Impact Speed Range of 10 km/h

The Cumulative Distribution Function (CDF) of the normal distribution is fitted to impact speed of the seriously injured pedestrians (146 cases) (Figure 4-3) in the PCDS database using maximum likelihood method. The CDF shows that 50% of the seriously injured pedestrian crashes occurred at impact speeds less than 45 km/h. The same figure shows that about 85% of the seriously injured pedestrian cases occur for impact speeds less than 70 km/h.

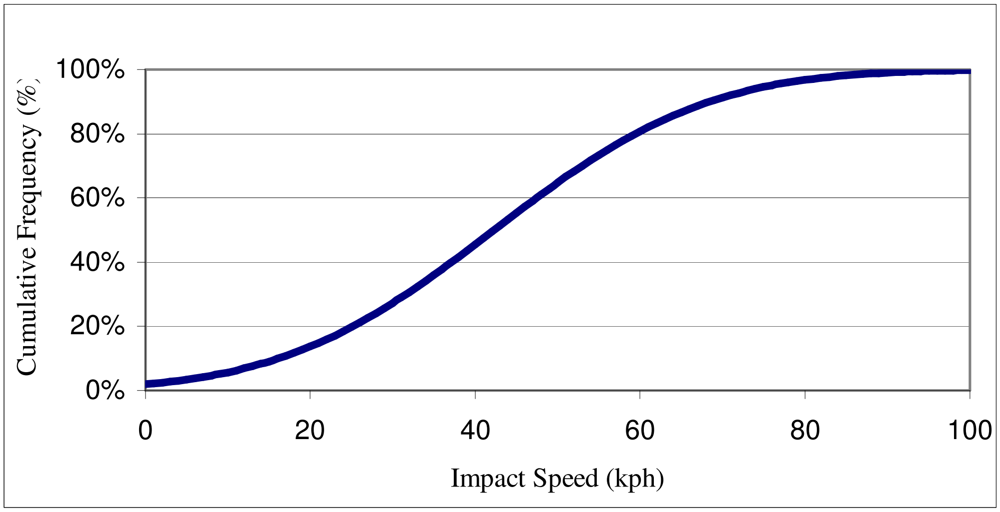


Figure 4-3: Normal Cumulative Distribution Function of Impact Speed for Seriously (MAIS3+) Injured Pedestrians in PCDS

For each impact speed, the number of seriously injured pedestrians is divided by the total number of pedestrians, producing an estimate of serious injury (MAIS3+) risk for each impact speed. This analysis shows two distinct areas of constant probability of MAIS3+ injury (Figure 4-4) at speed ranges of 15-25 km/h and 35-45 km/h. Therefore, the assumption of a continuous relationship between injury risk and impact speed used by Davis *et al.* (2002); Pasanen (1991) and previous research may not be valid. A significant number of physical parameters related to the pedestrian, vehicle, and the crash environment can result in this behavior. Clearly, this type of behavior does not lend itself to standard statistical analysis. Hence, a more expansive statistical analysis is described in the next segment and is used to develop a more appropriate risk model based on the present data.

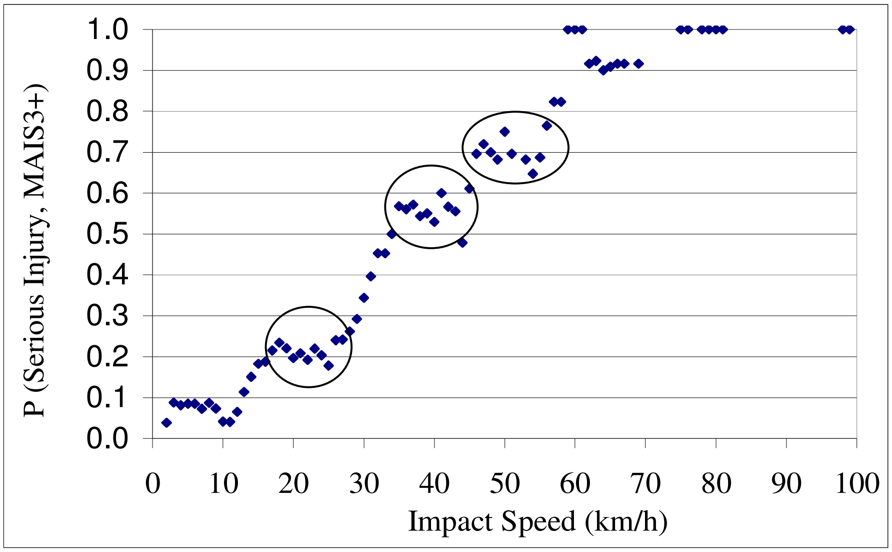


Figure 4-4: Risk of Pedestrian Serious Injury as a Function of Impact Speed Based on PCDS Data

4.2.2 Description of the Statistical Methods

First, the Cumulative Distribution Function of impact speeds and the risk function are compared to prove that the assumption that a CDF can be interpreted as a risk function is not valid. Second, the effect of error in impact speed estimation on the risk analysis is evaluated. Third, the non-continuous relationship between impact speed and pedestrian injury risk is demonstrated through the development of a non-parametric risk model. In summary, three different statistical methods will be applied for more in-depth analysis of the serious injury risk for pedestrians in the PCDS database.

4.2.2.1 Logistic Regression

The binary logistic regression is often used in developing risk functions when the outcome is dichotomous (binary). Kent (2004) used this type of regressions to develop injury risk functions from cadaver tests, where the predictors are the measurable stimuli, such as applied force, strain, deflection, and others. In the pedestrian data analysis, the severity of the pedestrian injury (serious vs. minor) is considered the dichotomous outcome to be modeled and the predictors are the impact speed, vehicle body type, and age.

The probability density function for the general logistic distribution is:

$$f(x) = \frac{e^{\frac{-(x-m)}{b}}}{b\left[1+e^{\frac{-(x-m)}{b}}\right]} \quad b \neq 0 \tag{4.1}$$

where m and b are the location and scale parameters solved for in a logistic regression.

The cumulative distribution function of the general logistic distribution is

$$F(x) = \frac{1}{1 + e^{\frac{-(x-m)}{b}}} \quad b \neq 0. \tag{4.2}$$

This can be written in the following format (Equation 4.3), which is used in SAS software, and for the binary outcome it is known as Binary Logistic Regression:

$$F(x) = \frac{e^{ax+b}}{1 + e^{ax+b}} \tag{4.3}$$

where a and b are the parameters of the logistic regression and x the predictor.

A risk function defines the injury probability as a function of measurable or known predictors (e.g., age, gender, mass, seat belt loading, applied force, impact energy, or others). The development of risk functions is the main purpose of biomechanical testing and the field of injury biomechanics. For the purpose of this study, vehicle impact speed and vehicle type will be assumed to be the measurable predictors while developing injury risk functions for pedestrians.

Serious injury risk functions developed by the logistic regression described above (Equation 4.3) for each body region (head, thorax and lower limb) and for the overall outcome will be compared with the normal cumulative density distribution function (CDF) of the impact speed of the serious injury cases.

4.2.2.2 Uncertainty in Reliability/Survivability Analysis

Injury risk functions are statistically derived estimations of the probable risk of injury from a certain stimulus. As a result, the only outcome possible is whether an injury to the specimen occurs or not for that given stimulus. If an injury occurs, it is generally not possible to determine if the stimulus was just enough or substantially higher than that to produce the injury in the specimen tested. This type of biomechanical data is considered censored (Prasad *et al*., 2006).

By analogy, the vehicle impact speed is considered that "stimulus" and therefore the speed data will be considered censored and there will be a need to use reliability/survival analysis and not the binary logistic regression analysis.

A data point is right-censored if injury has not occurred and it is unknown how much more stimulus (e.g., impact speed) could be tolerated before injury occurred. A data point is left-censored if injury has occurred and it is not known how much less stimulus would have caused the injury. A data point is termed uncensored or accurate if injury occurred exactly at the value of the stimulus measured.

Impact speeds for uninjured cases are right censored with the lower bound being the impact speed estimate and the upper bound being infinity. The impact speeds for the seriously injured cases are left censored with a lower bound of 0 km/h and an upper bound equal to the speed estimate.

The development of continuous risk functions is facilitated by the *a priori* assignment of a form of the risk function, the coefficient of which can be determined using least squares, maximum likelihood, or some other method to maximize the function’s fit to the data. This parametric approach to risk function development is common in the literature and several statistical distributions have been used to define the functional form. Examples of these distributions are the Lognormal, Logistic, Weibull and Normal distributions.

The impact speed as estimated in the PCDS database has an inherent error indicated by an accuracy range. Therefore, there is a need to introduce the error in the impact speed estimate while developing injury risk functions for pedestrians. Adding or subtracting the error led to two different risk curves other than the curve that does not take into considerations the error in the speed estimate. The three curves are called in the result section, lower, no error, and upper.

4.2.2.3 Non-parametric Injury Risk Function

The non-continuous relationship between serious injury risk and the impact speed as described earlier (Figure 4-4) has led to the usage of a non-parametric distribution analysis to capture this phenomenon, while a parametric distribution can not since it smoothes the risk to fit a continuous function defined as the cumulative distribution function (CDF) of the best fitted distribution (e.g. Normal, Weibull or Lognormal). The non-parametric risk function is performed on the cases without correction for the error in impact speed estimation.

4.2.3 Results

The three statistical methods described above were performed on the 412 PCDS cases using the Minitab software (Minitab 15 Statistical Software, Minitab, Inc.) and SAS software.

The results of PCDS data analysis are presented with a focus on clearly showing what is being done that is different from the past analysis and what the comparisons reveal, and then presenting the main outcome of the risk functions for pedestrian injury as a function of impact speed and vehicle type.

4.2.3.1 Comparison Between Cumulative Distribution Function and Logistic Regression

Normal cumulative distribution functions for impact speed for the MAIS3+ and individual body regions (head, thorax and lower limbs) AIS3+ cases are compared with the binary logistic regression model (Figures 4-5 to 4-8). The purpose of this comparison is to examine the validity of use of cumulative distribution function, reported in previous studies (Ashton, 1979; Lefler, 2004), as a risk function. The parameters a and b of the logistic regressions as presented in Equation 4.3 , as well as the Goodness-of-fit tests are represented in Table 4-2 for final outcome as well as the severity of injury by body region.

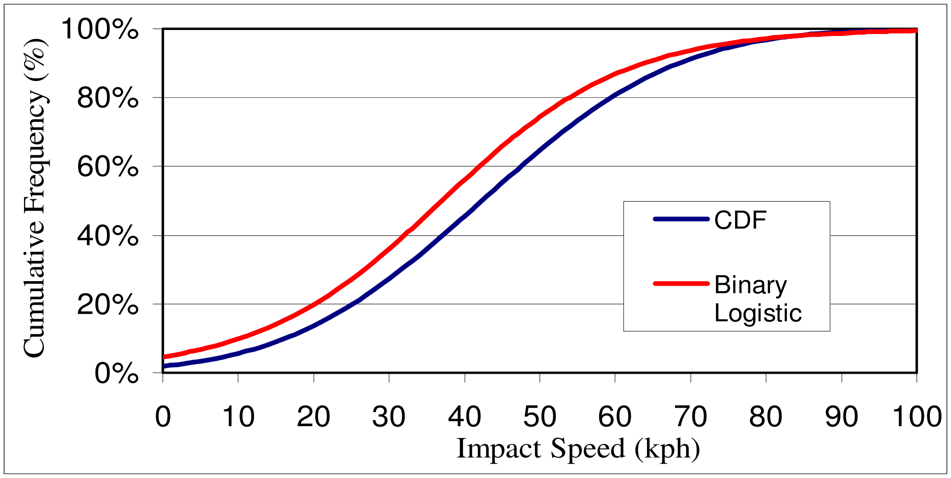


Figure 4-5: Normal Cumulative Distribution Function of Impact Speed for Pedestrians with MAIS3+ Injury vs. Logistic Regression of MAIS3+ Cases

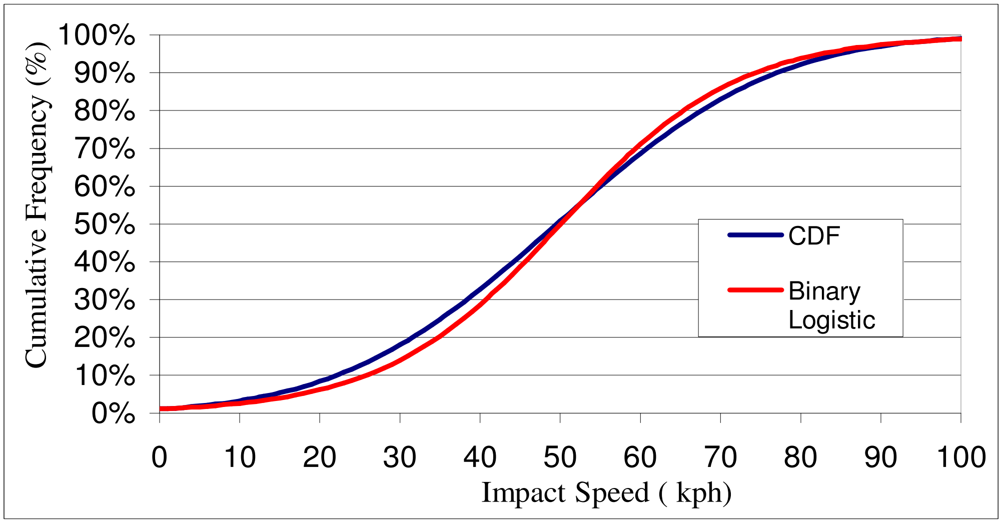


Figure 4-6: Normal Cumulative Distribution Function of Impact Speed for Pedestrians with AIS3+ Head Injury vs. Logistic Regression of Head AIS3+ cases

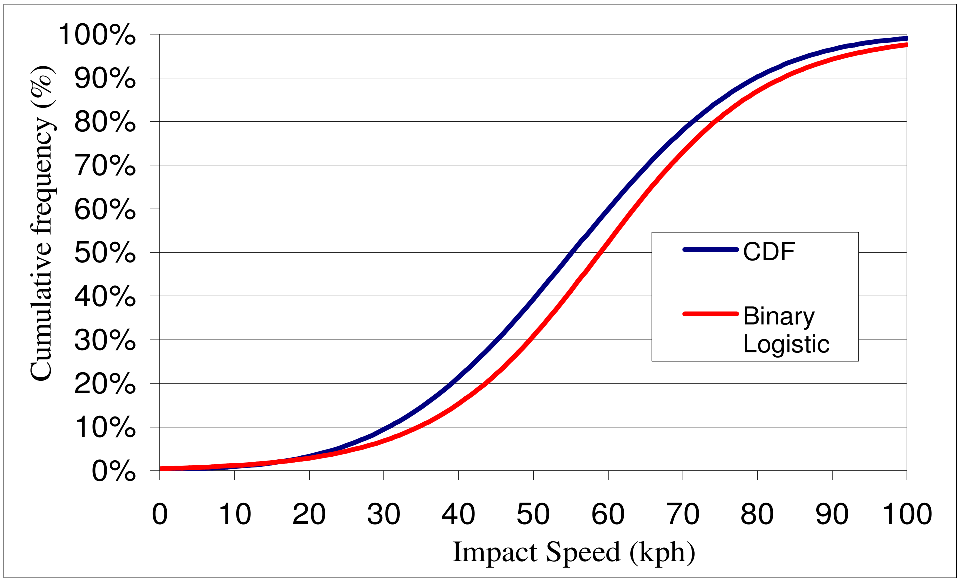


Figure 4-7: Normal Cumulative Distribution Function of Impact Speed for Pedestrians with AIS3+ Chest Injury vs. Logistic Regression of Chest AIS3+ Cases

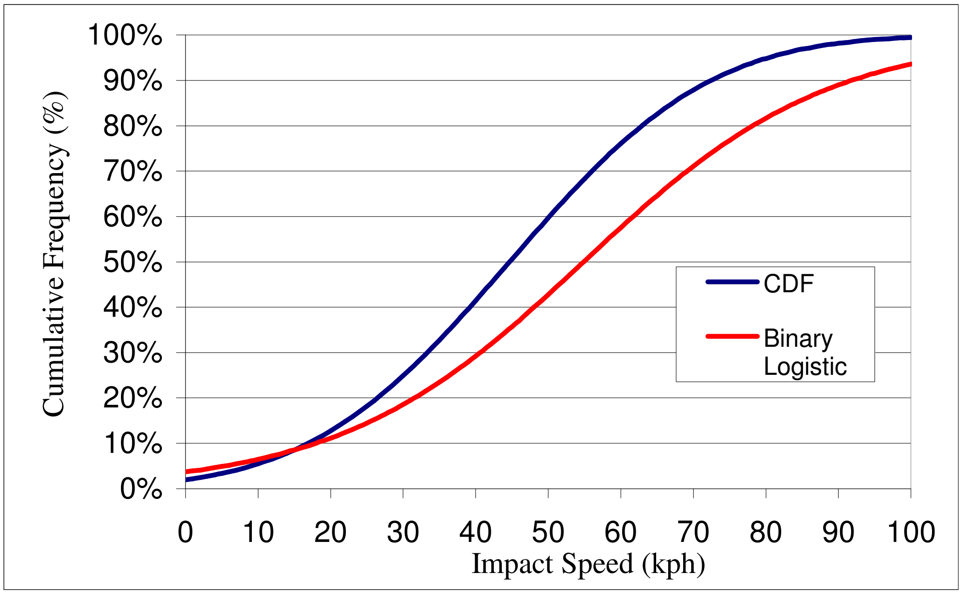


Figure 4-8: Normal Cumulative Distribution Function of Impact Speed for Pedestrians with AIS3+ Lower Limb Injury vs. Logistic Regression of AIS3+ Chest Injury Cases

Table 4-2: Parameter Estimate and Goodness-of-fit of Logistic Regressions for Serious Injury Cases by Body Region

Binary Logistic	Yes	No	a	p-value
MAIS3+	146	269	0.0819	<0.0001
Head AIS3+	85	330	0.0879	<0.0001
Chest AIS3+	54	361	0.0901	<0.0001
Lower Limb AIS3+	88	327	0.0594	<0.0001
Binary Logistic	b	p-value	log-likelihood	Chi-Square
MAIS3+	-3.035	<0.0001	-198.304	72.4769
Head AIS3+	-4.371	<0.0001	-141.693	71.7699
Chest AIS3+	-5.315	<0.0001	-102.521	71.0878
Lower Limb AIS3+	-3.263	<0.0001	-173.647	74.5388

Impact speed is found to be significant predictor of the injury severity for all body regions for pedestrians at 95% confidence level. The p values (<0.001) are less than 0.05 resulting in rejecting the null hypothesis that impact speed is not a significant predictor.

The cumulative distribution function is based on a normal distribution fit for the impact speed of seriously injured cases. Table 4-3 shows the parameters of the normal distribution used to model the cumulative distribution function of impact speed for seriously injured cases by body region.

Table 4-3: Parameters Estimate of the Normal Cumulative Distribution Function fit for Serious Injury Cases by Body Region

Normal CDF	Cases	Mean	Standard deviation
MAIS3+	146	42.3	20.4
Head AIS3+	85	49.6	21.4
Chest AIS3+	54	55.2	19.7
Lower Limb AIS3+	88	44.6	21.6

It is clear that the cumulative distribution function of impact speed for MAIS3+ injury cases does not match the logistic regression (Figure 4-5). For example, 64% of the MAIS3+ cases occurred at impact speed of 50 km/h or less while the risk of a pedestrian being hit by a car at 50 km/h is 74%. There is a vertical shift of the risk curve by approximately 10% from the cumulative distribution function.

This difference between CDF and risk function is minimal but noticeable for head and chest injuries. For these two body regions, a normal CDF can be used to estimate the risk of an AIS3+ injury. However, this comparison for the lower limb injuries is easily noticeable (Figure 4-7). Hence, it is not appropriate to use a Normal Cumulative Distribution Function of impact speeds to predict the risk of an injury at certain speed. Almost all previous studies have developed cumulative distribution functions for impact speed for the target cases (either fatal or seriously injured) and did not perform a risk type of analysis that takes into consideration all cases (injured and non-injured) .

4.2.3.3 Effect of Vehicle Body Type on Injury Severity

Multivariate regression analysis of the PCDS database has led to the conclusion that only the vehicle body type (e.g. Passenger Cars vs. Light Trucks Vehicles) is found to be a significant predictor of injury severity for pedestrians when added to impact speed in the regression equation.

The predominant conclusion in the literature (Lefler, 2004) is that Pedestrians are at greater risk to sustain a serious injury when struck by a Light

Truck Vehicle (LTV) compared to passenger cars. This conclusion is statistically valid in PCDS for the maximum sustained injury (MAIS3+) and for chest injuries (Chest AIS3+) because the lower limit of 95% confidence of the odd ratio for the risk between LTVs and passenger cars is greater than one (Table 4-4). A pedestrian is 1.9 times more likely to sustain a serious injury and 2.7 times more likely to sustain a chest serious injury if struck by an LTV compared to passenger car.

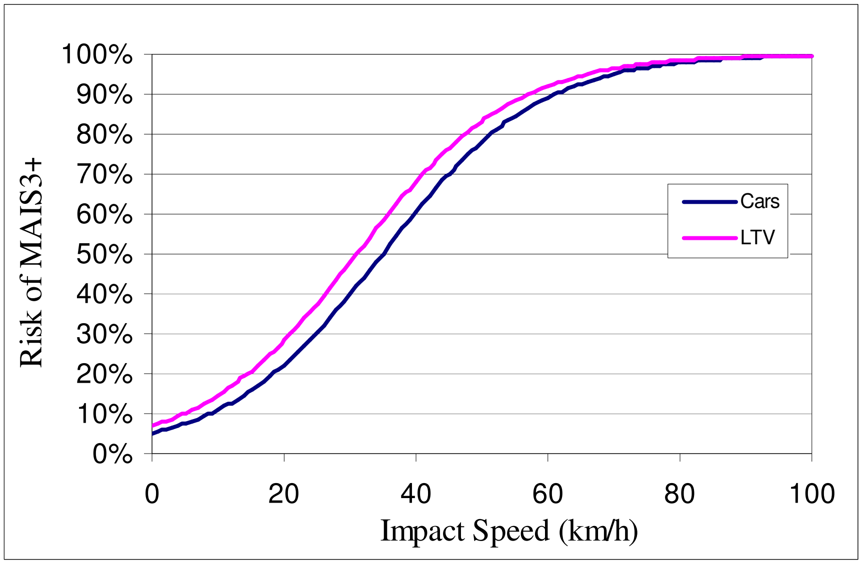


Figure 4-9: Risk of MAIS3+ by Vehicle Type

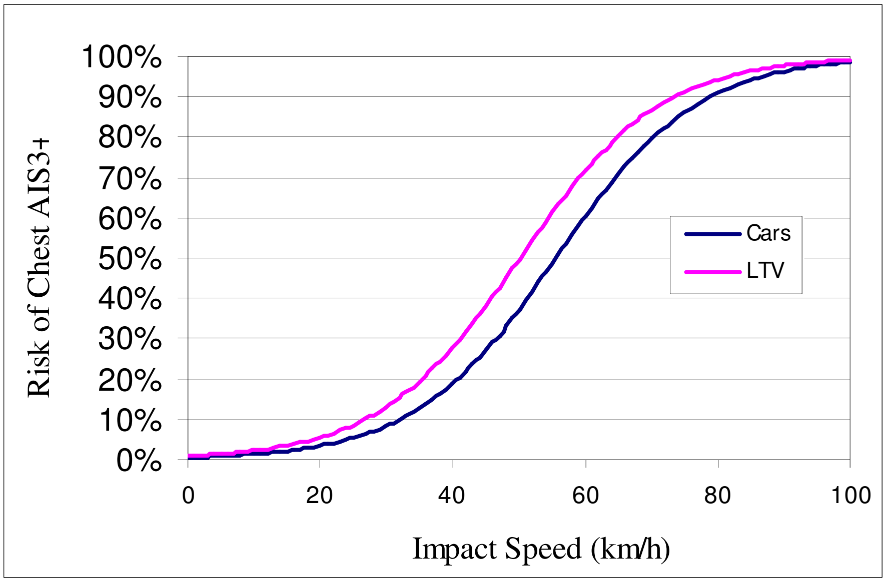


Figure 4-10: Risk of Chest AIS3+ by Vehicle Type

Table 4-4: Odd Ratios of Serious Injury Risk for LTV vs. Passenger Cars

	Point Estimate	95% Wald Confidence Limits		Chi - Square	p-value
Risk of MAIS3+	1.905	1.054	3.442	4.5531	0.0329
Risk of Head AIS3+	1.255	0.589	2.673	0.3476	0.5555
Risk of Chest AIS3+	2.755	1.163	6.525	5.3050	0.0213

4.2.3.3 Pedestrian Injury Risk Function with Uncertainty in Predictor Estimates

A survivability/reliability analysis is performed on the 412 cases in this study for the overall MAIS3+ as well as separately for head, chest, and lower limb. The error in the impact speed estimate is taken into consideration and it results in lower and upper bound risk curves for this analysis and is shown in Figure 4-11. Table 4-5 shows the results of the parametric distribution analysis by body region and Table 4-6 contains the correlation coefficient of the best fitted distribution for the whole body and specific regions, namely head, chest, and lower limb. The results for these body regions are plotted in Figures 4-12, 4-13 and 4-14, respectively.

The risk functions for different body regions are sensitive to impact speed error. Therefore, there is a need to investigate other sources where more accurate impact speeds have been estimated. This can be observed in Figure 8 as the risk of a pedestrian sustaining an MAIS3+ injury when hit by a vehicle at 50 km/h can vary between 65% and 83%.

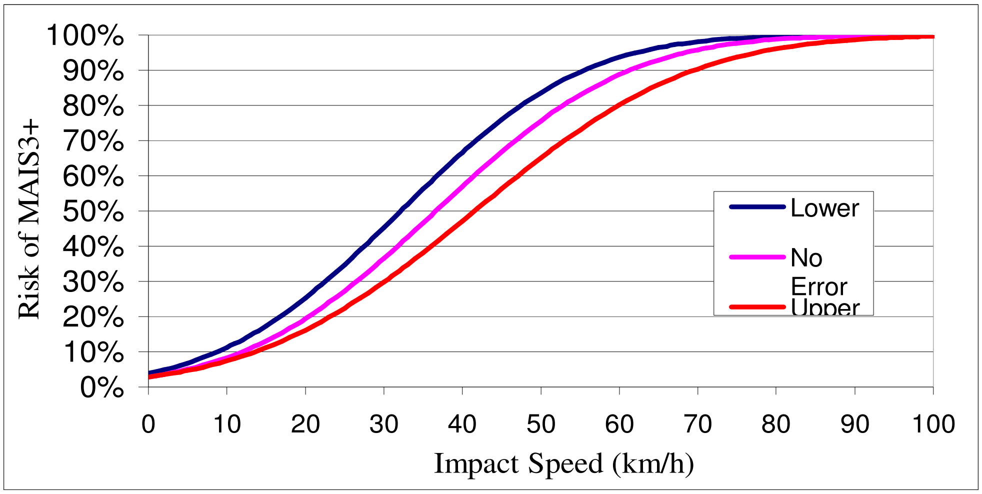


Figure 4.11: Risk of MAIS3+ Injury vs. Impact Speed under Uncertainty

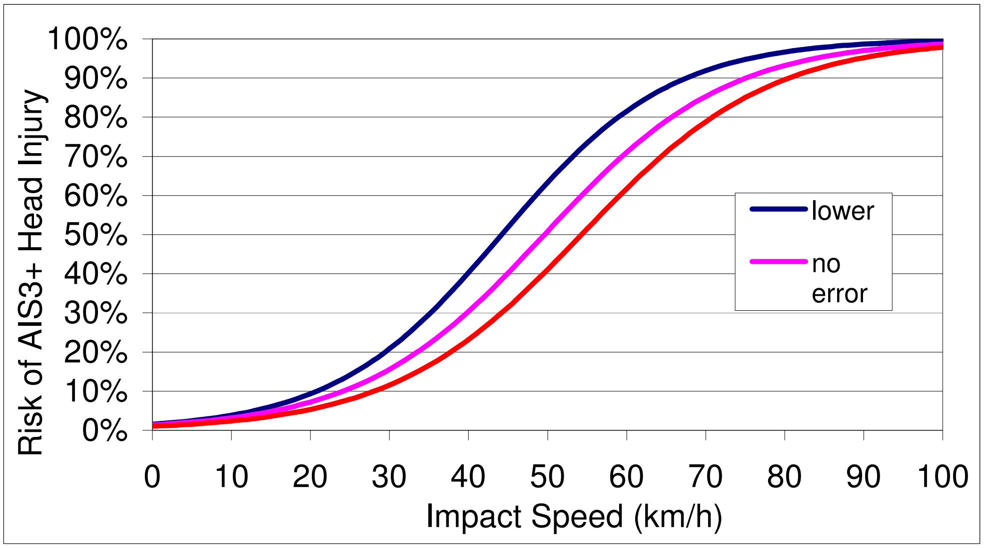


Figure 4-12: Risk of AIS3+ Head Injury under Uncertainty

Table 4-5: Parametric Distribution Analysis by Body Region

	Distribution	Lower Estimate	No Error	Upper Estimate
MAIS3+	Normal	$\mu=32.11$ $\sigma=18.23$	m=36.62 $\sigma = 19.27$	$\mu=41.54$ $\sigma = 21.82$
Head AIS3+	Logistic	m= 4.20 b= 10.63	m= 49.61 b= 11.60	m= 54.29 b= 11.94
Chest AIS3+	Weibull	$\alpha= 2.88$ $\beta= 59.31$	$\alpha= 3.19$ $\beta= 64.75$	$\alpha= 3.31$ $\beta= 70.48$
Lower Limb AIS3+	Normal	$\mu=49.17$ $\sigma=27.41$	$\mu=54.74$ $\sigma =28.89$	$\mu=59.59$ $\sigma = 29.51$

Table 4-6: Correlation Coefficients of Parametric Distribution by Body Region

	Distribution	Lower Estimate	No Error	Upper Estimate
MAIS3+	Normal	0.963	0.965	0.974
Head AIS3+	Logistic	0.963	0.976	0.974
Chest AIS3+	Weibull	0.979	0.970	0.971
Lower Limb AIS3+	Normal	0.963	0.977	0.960

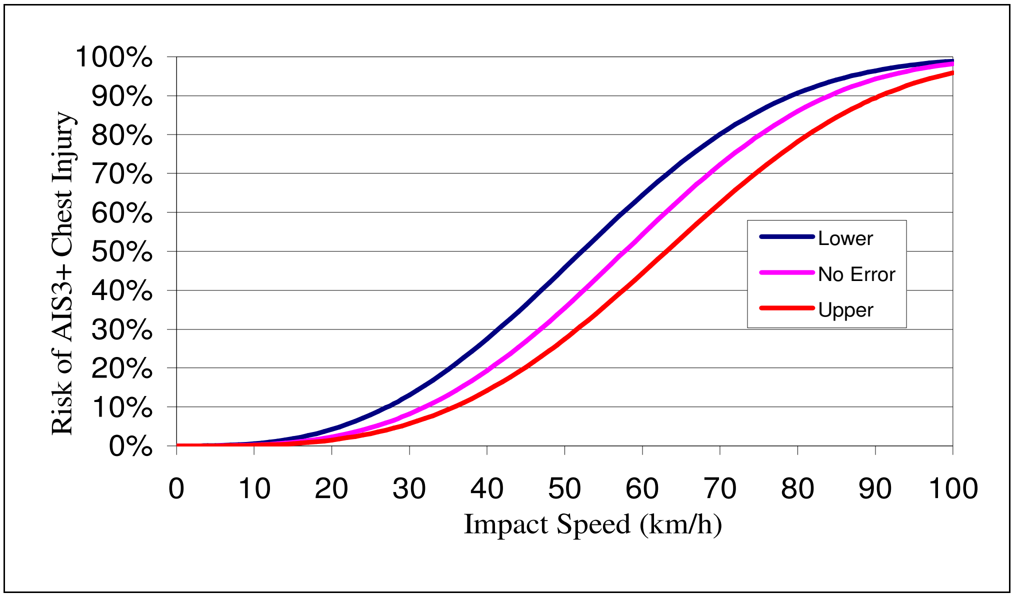


Figure 4-13: Risk of AIS3+ Chest Injury under Uncertainty

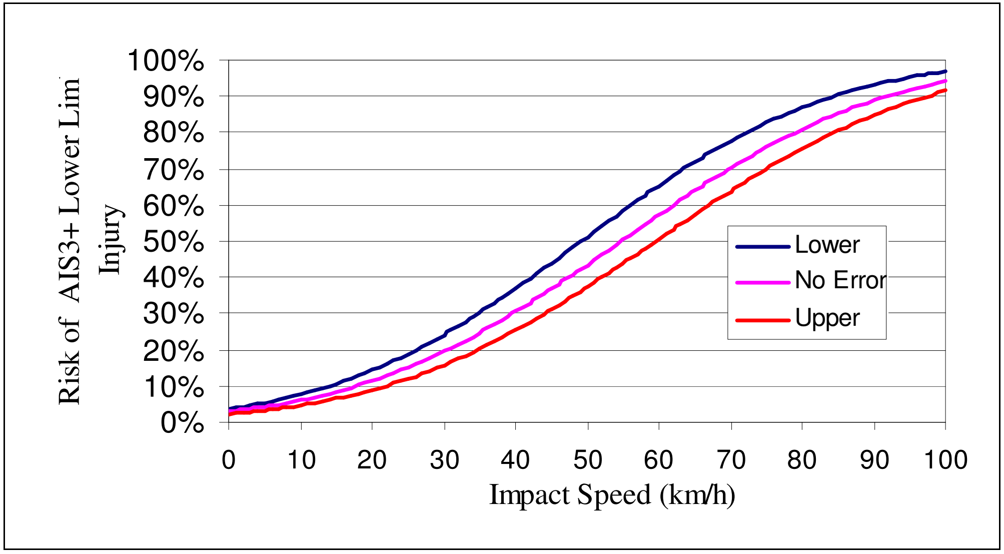


Figure 4-14: Risk of AIS3+ Lower Limb Injury under Uncertainty

4.2.3.4 Empirical Risk Function for Maximum Likelihood of Pedestrian Injury

The relationship between the vehicle impact speed and the fatality risk for pedestrians from the PCDS data as described above may not be continuous due to the dynamics of a pedestrian crash and biomechanical properties of the human body and therefore a non-parametric distribution could capture this phenomenon if it exists. This model is called an empirical maximum likelihood risk function.

The non-parametric distribution shows several regions where serious injury risk value remains relatively constant considering the uncertainty in the data (Figure 4-15). Two regions, between 16 and 30 km/h and 38 to 48 km/h show this relatively constant risk values more pronouncedly. In the first region, the serious injury risk remains relatively constant at around 22 % while for the second region (38 to 48 km/h) the value of risk is about 70%. This observation strengthens the argument made earlier that the CDF approach to data analysis masks the information contained in the data and that there may be critical speed ranges that can be identified. Furthermore, the constant risk value points to the fact that, in these regions, other factors associated with the vehicle, pedestrian, and environment of the crash have a pronounced effect on the relationship between injury and impact speed.

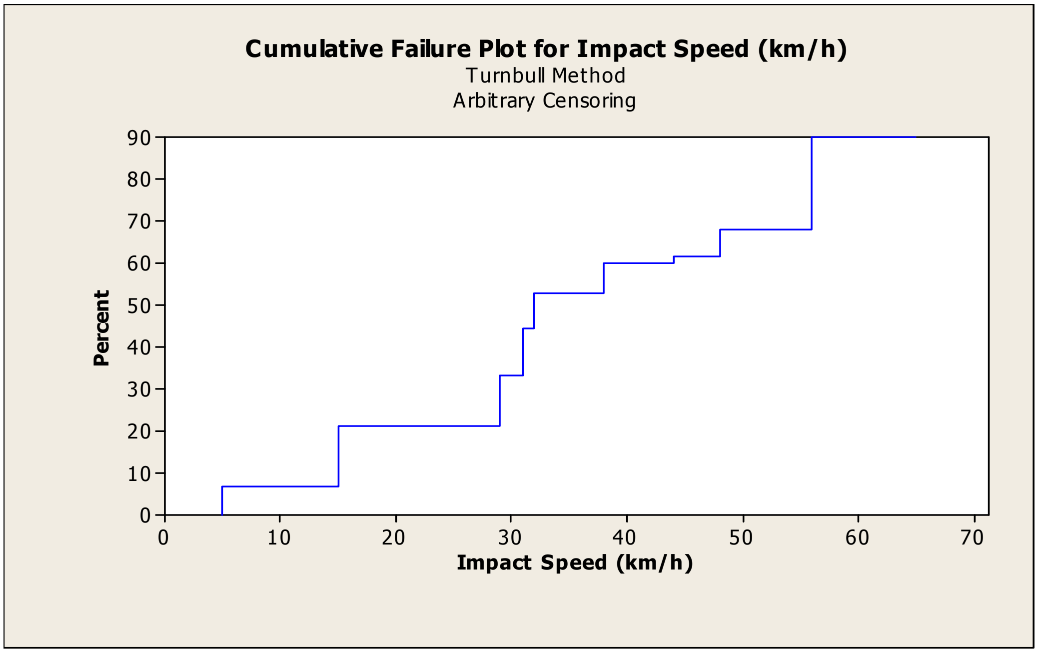


Figure 4-15: Non-Continuous Model for Pedestrian Serious Injury (MAIS3+) Risk Using NASS-PCDS Database

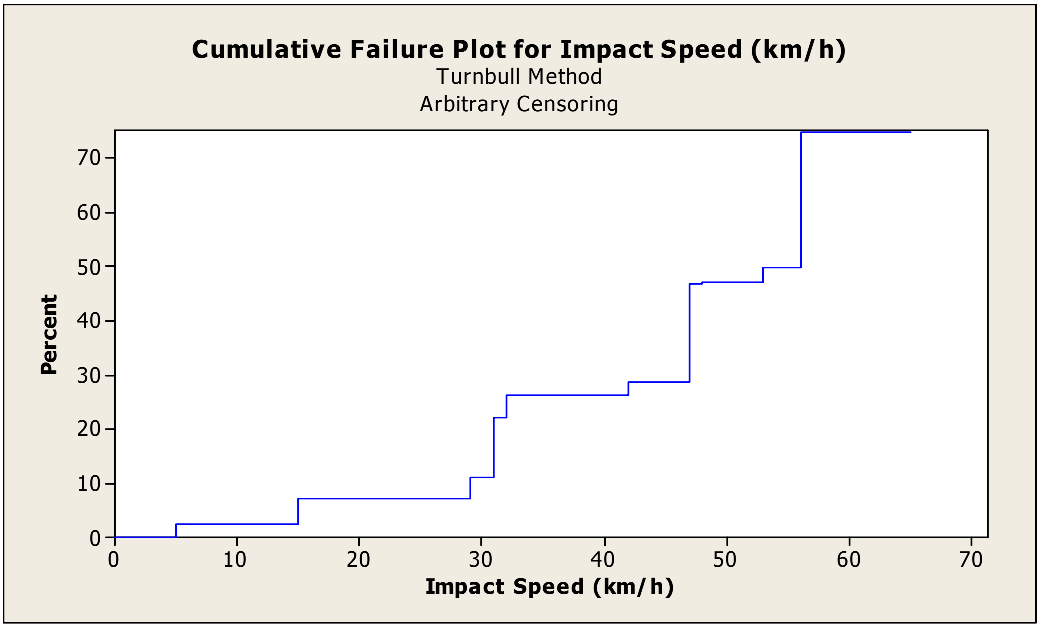


Figure 4-16: Non-Continuous Model for Pedestrian Head Serious Injury (AIS3+) Risk Using NASS-PCDS Database

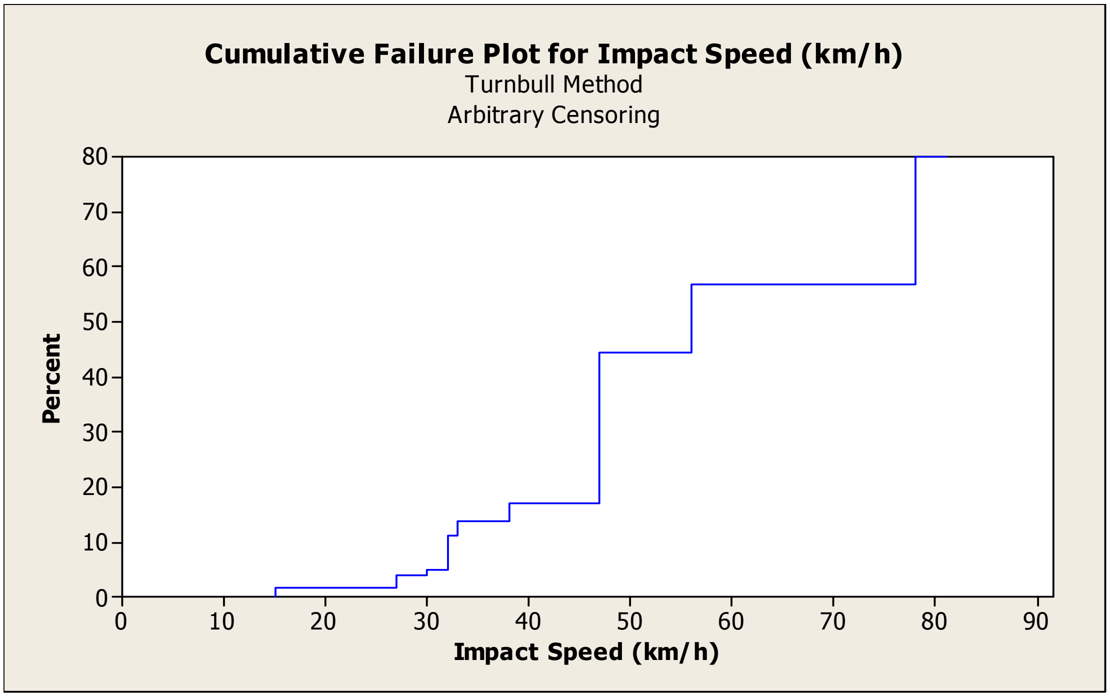


Figure 4-17: Non-Continuous Model for Pedestrian Chest Serious Injury (AIS3+) Risk Using NASS-PCDS Database

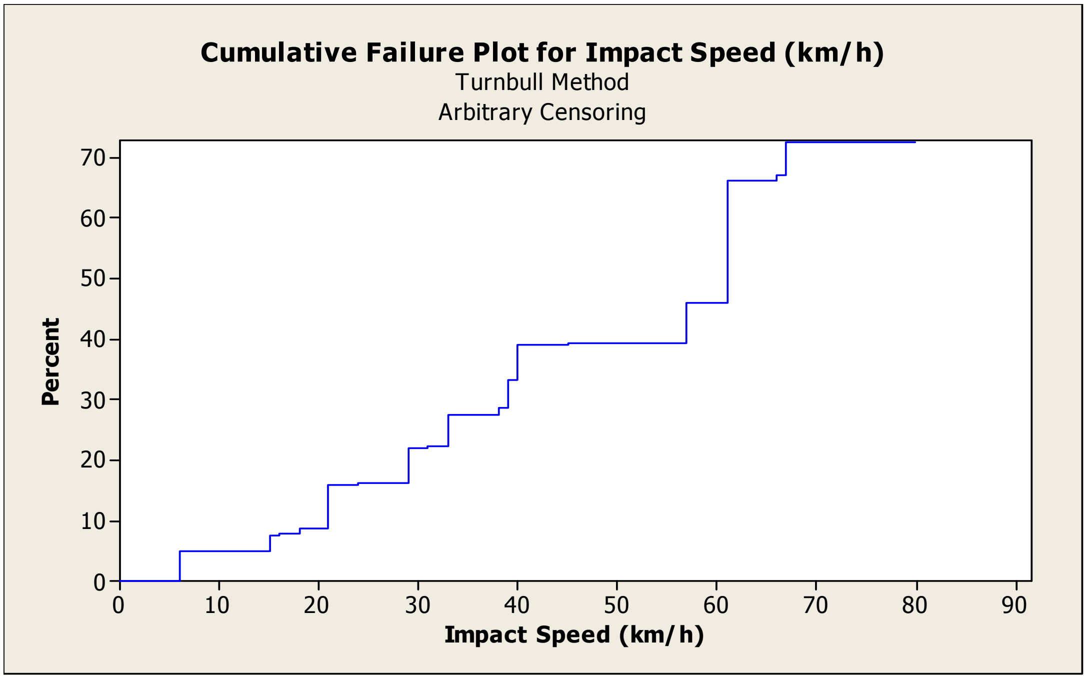


Figure 4-18: Non-Continuous Model for Pedestrian Lower Extremities Serious Injury (AIS3+) Risk Using NASS-PCDS Database

4.3 Development of Pedestrian Injury Risk Functions Using Simulations

The objective of this section is to carry out an analysis of pedestrian collision with a passenger car and explain the sharp increase in risk of serious injury observed in the PCDS data analysis between 30 km/h and 50 km/h (Figure 4-9 and 4-12) and to explain the constant head AIS3+ risk areas seen in PCDS (Figure 4-16). The simulations are not expected to develop pedestrian injury risk functions for all scenarios that affect pedestrian injury (i.e. age, vehicle type, initial position, etc.).

The MADYMO biodynamic simulation software (TNO, 2005) is used to perform the pedestrian crash simulations. Injury criteria for these three body regions (head, thorax, and lower extremities) will be outputted and injury risk functions will be developed and compared to those derived from the PCDS database and presented earlier.

There were 542 AIS3+ injuries sustained by the 412 pedestrian that form the sample analyzed earlier. Head AIS3+ injuries consist of about 45% of these AIS3+ injuries, compared to 26% lower limbs AIS3+ injuries and 14% AIS3+ chest injuries.

The risk of a pedestrian sustaining a head AIS3+ injury is greater than the risk of sustaining a chest AIS3+ injury for all impact speeds and greater than the risk of lower limbs AIS3+ injury for the speeds higher than 40 km/h. This latter result is trivial because one would expect lower limbs AIS3+ injuries for relatively low impact speeds. Around 99 % of the lower limbs AIS3+ injuries were AIS3 injuries, which may result in long-term disability but do not cause high threat to life. An AIS3 injury represents 6% threat to life.

4.3.2 Theory of Modeling Techniques

MADYMO (MAthematical DYnamic MOdels) is a computer program used to simulate the dynamic behavior of physical systems and was originally created to study occupant behavior during automotive accidents. This is accomplished through the use of both rigid body dynamics and finite element modeling. A MADYMO model consists of bodies that can be connected to one another by a joint to form a multi-body system. Joints restrict the relative motion between two bodies based on the joint type or degrees of freedom between the bodies.

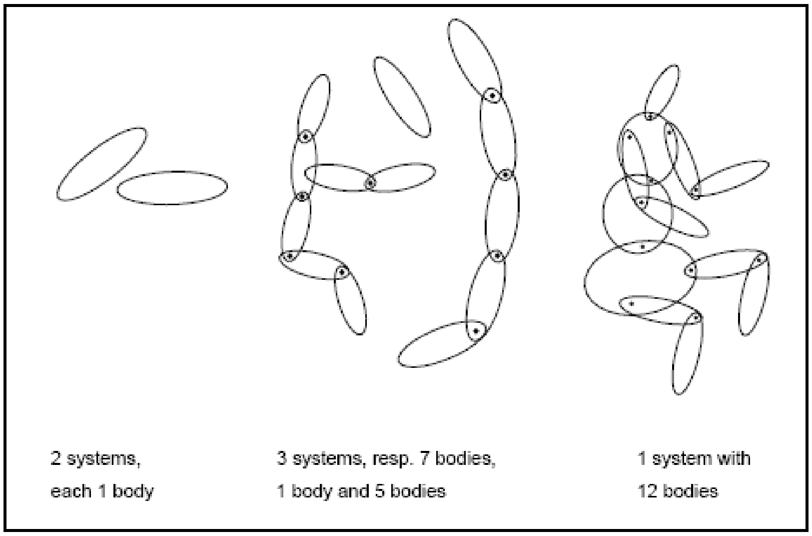


Figure 4-19: Examples of Single and Multi-Body Systems [MADYMO Theory Manual]

Each rigid body is defined by its mass, location of the center of gravity, and the moments of inertia and products of inertia. The geometry of the body is not required for the equations of motion except for contact purposes. In these cases, the shape of the geometry is defined by attaching a ‘surface’ to the body in the form of a plane, ellipsoid, cylinder, or faceted (finite element) surface.

MADYMO contains a database of pedestrian human models that have been validated against the results of Post Mortem Human Subjects PMHS tests (Yang, 2000; Ishikawa, 1993)

An average male pedestrian model was developed first. The anthropometry of this model is similar to the facet occupant models, based on the database of the AMSIS software package (RAMSIS, 1997). Like for the facet occupant models, the Western European population aged 18-70 years in 1984 has been used. Afterwards, the mid-size male pedestrian model has been scaled towards a 3-year-old child; a 6-year-old child, a small female, and a large male model (see Figure 4-20).

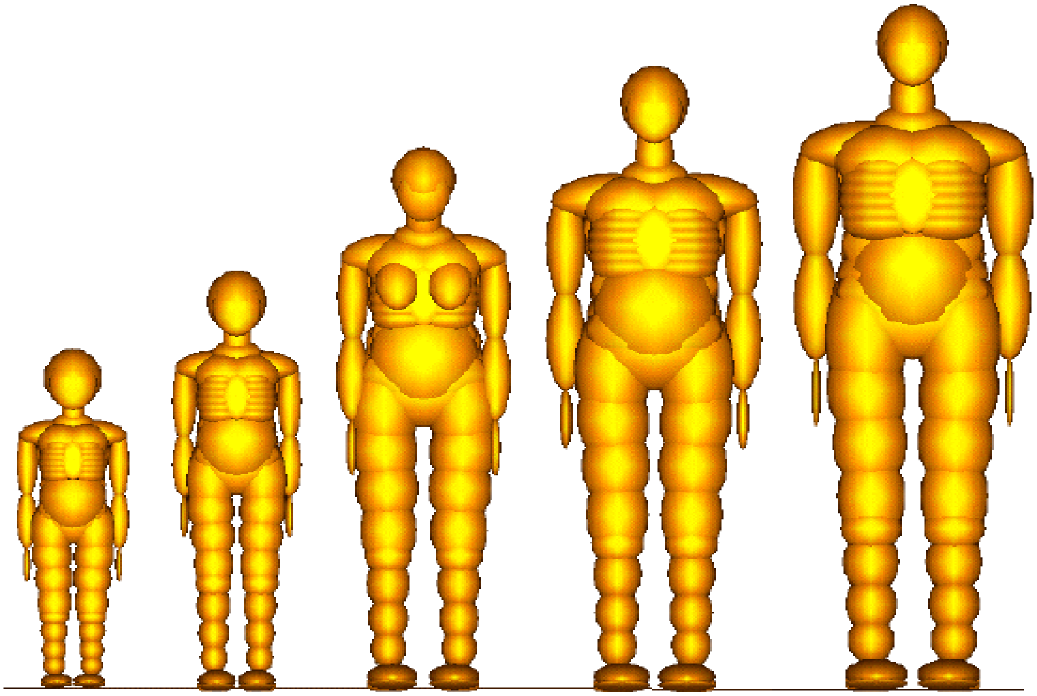
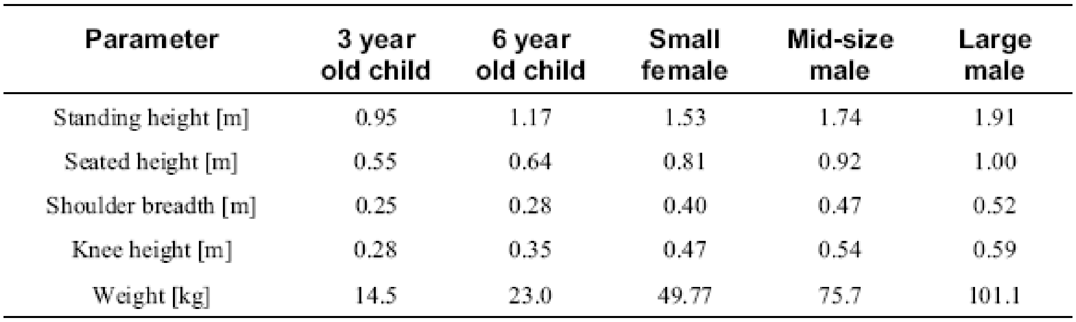


Figure 4-20: The Pedestrian Family, from Left to Right: the 3-Year Old Child, the 6-Year Old child, the Small female, the Mid-Size Male and the Large Male Model

The anthropometries of the small female and large male pedestrian models are also based on the RAMSIS database. The anthropometries of the 3- and 6-year-old child are based on the specification of the Q child dummies. Global anthropometry specifications are given in table 5.

The pedestrian models each consist of 52 rigid bodies, organized in 7 configuration branches. The outer surface is described by 64 ellipsoides and 2 planes. The first branch connects the head and thorax to the pelvis. The second and third branches connect the bodies of the left and right arm to T1, respectively. The fourth and fifth branches connect the bodies of the left and right leg to the pelvis, respectively. The heels are each connected to the mid-foot joint by a separate branch.

Table 4-7: Anthropometry of the Pedestrian Models



Parameter	3 year old child	6 year old child	Small female	Mid-size male	Large male
Standing height [m]	0.95	1.17	1.53	1.74	1.91
Seated height [m]	0.55	0.64	0.81	0.92	1.00
Shoulder breadth [m]	0.25	0.28	0.40	0.47	0.52
Knee height [m]	0.28	0.35	0.47	0.54	0.59
Weight [kg]	14.5	23.0	49.77	75.7	101.1

Source: MADYMO Human Models Manual, Release 6.4

Injury risk functions are developed for the Mid-size male and the 6-year old child pedestrian models.

4.3.2 Model of Passenger Car

The vehicle model chosen for the simulations is the Rover 25 due to the availability of a MADYMO model for this vehicle and its detailed contact characteristics. The Rover 25 series is modeled as one body which consists of eleven ellipsoids for spoiler, bumper, windscreen, roof, and top. The model was developed by Rong Guo at the Birmingham Automotive Safety Center (BASC) and the contact characteristics of the vehicle are obtained from the EU project APROSYS Deliverable Report D312B (APROSYS SP3, 2006) and presented in Figures 4-23 to 4-25.

Figure 4-21: Rover 25

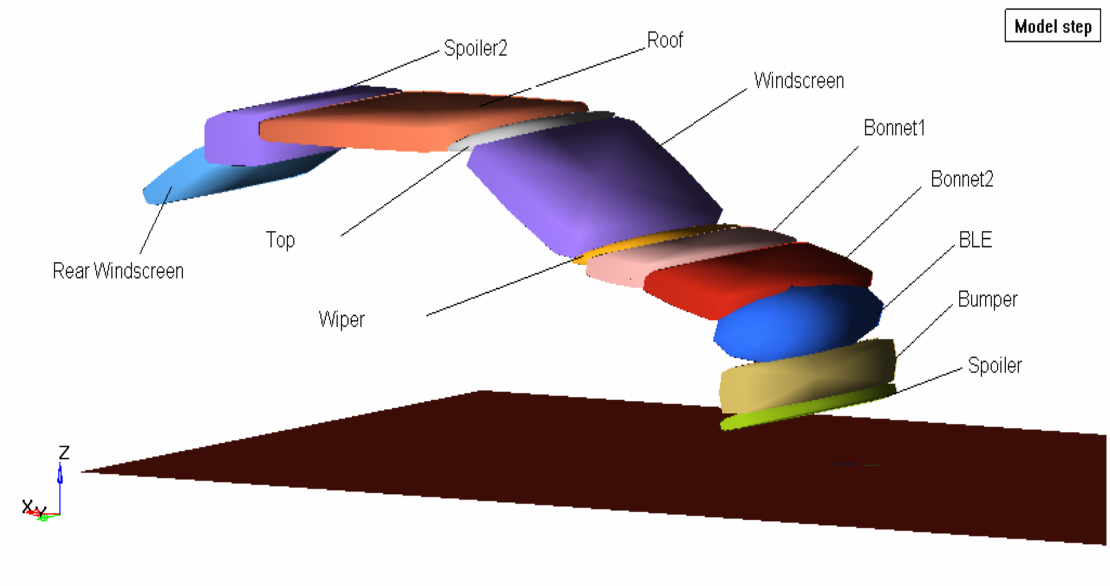


Figure 4-22: MADYMO Model of the Rover 25

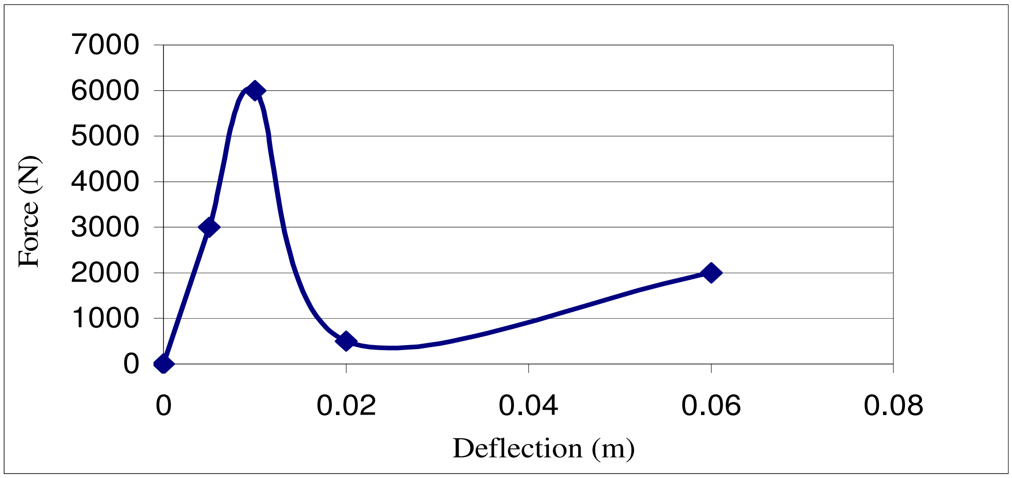


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Figure 4-23: Windscreen Stiffness

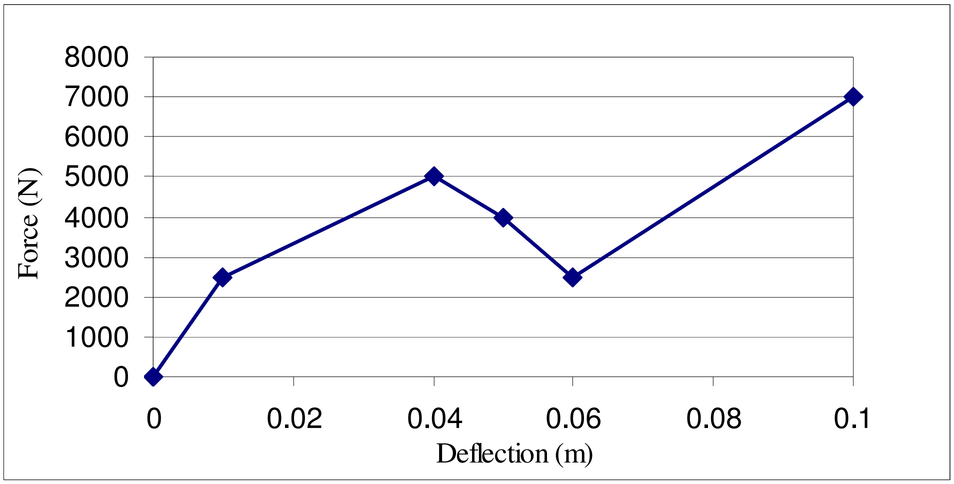


Figure 4-24: Hood Stiffness

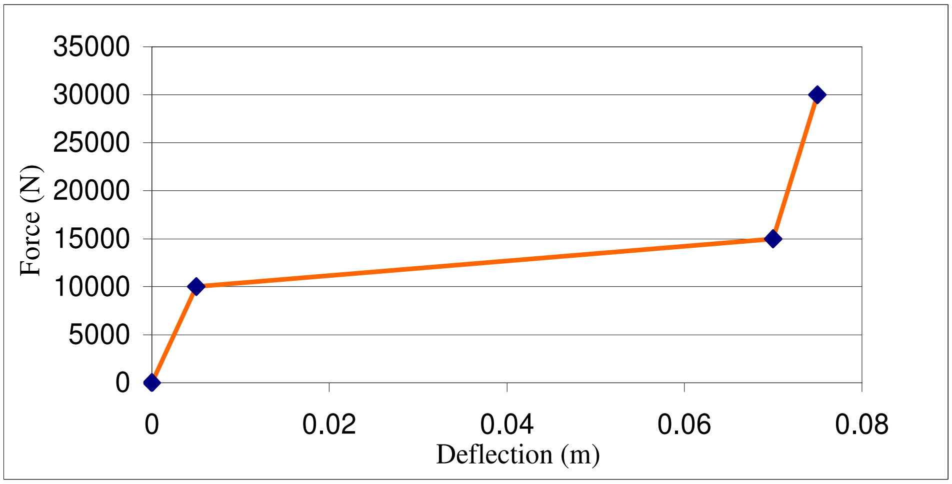


Figure 4-25: Bumper Stiffness

4.3.3 Pedestrian Positioning and Vehicle Impact Speed

Considering that in real-world crashes many pedestrians are hit while crossing the road, the simulations are set up so the vehicle strikes the right side of the mid-size male pedestrian who is in a walking position with 100% of his weight on the right foot before the impact as shown in figures 4-26.

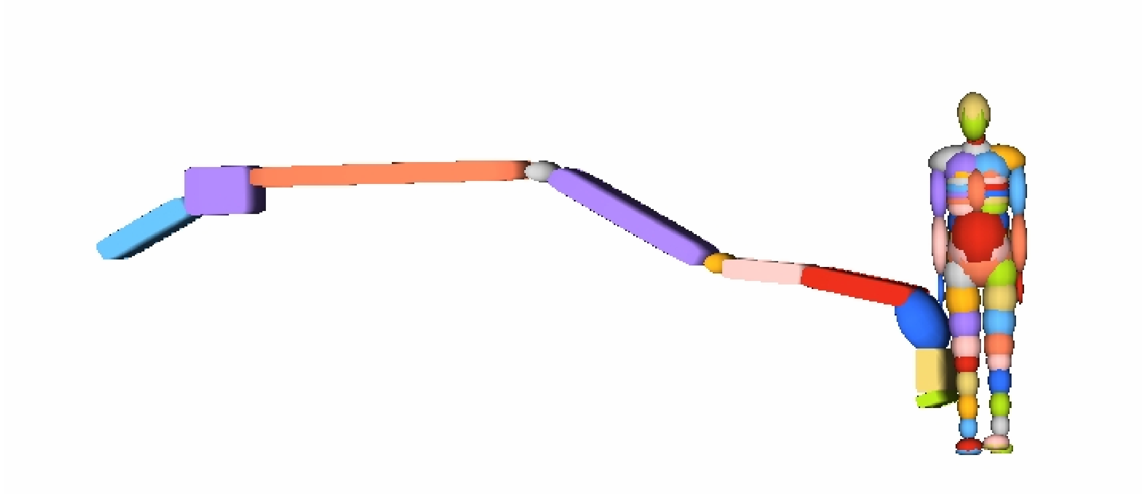


Figure 4-26: Initial Position of the Mid-Size Male Pedestrian Model

Another position is used in the simulations where the pedestrian is in erect standing position where the vehicle impacts the pedestrian on the right side; a configuration that leads to 50/50 weight distribution on both feet.

Children sustain chest injury from the first contact with a vehicle due to their height, therefore the 6-Year Old Child dummy is positioned in an erect standing position facing the vehicle, the dummy will behave better and the frontal impact injury criteria can be used in this position as shown in Figure 4-27.

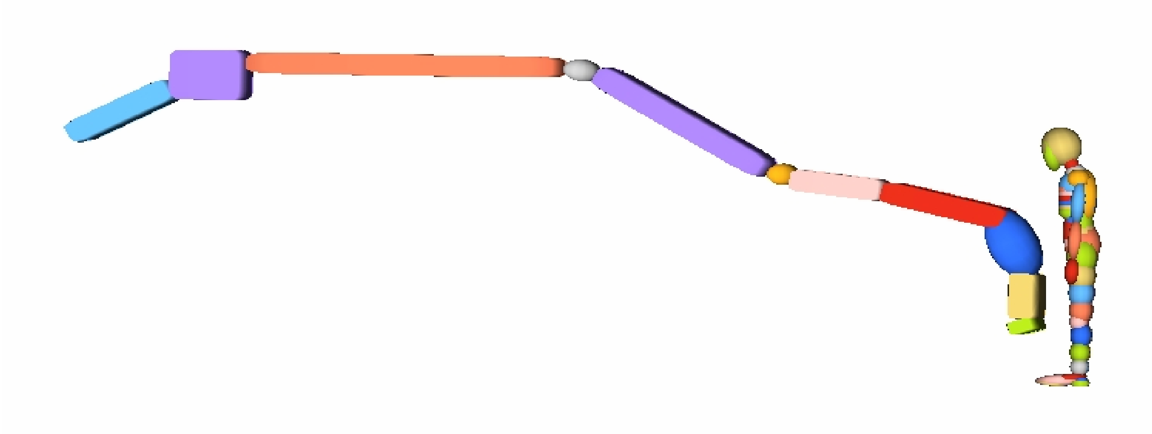


Figure 4-27: Initial Position of the 6-Year Old Child Pedestrian Model

The pedestrian model for the mid-size and the 6-year old configurations is positioned near to the front of the vehicle and the impact speed varies between 5 and 80 km/h with a 5 km/h increment, which results in 16 simulations for each pedestrian model (total of 32 simulations). The vehicle strikes the pedestrian at the intended impact speed while decelerating at 7 $m/s^{2,}$ which is a typical deceleration value for emergency braking without ABS (Kudarauskas, 2007). The simulation time is 1 second; however, all the injuries are outputted from the first contact between the pedestrian and the vehicle.

4.3.4 Kinematics of the Mid-size Male Pedestrian Model

In pedestrian-vehicle impacts, the front shape of the vehicle, stiffness of different parts, impact speed, and pedestrian height affect the kinematics and propensity of pedestrian injuries. The Rover 25 is a small car with hood front hitting the upper leg of the mid-size male pedestrian model, therefore, there are more head and lower extremities injuries risk than thorax and pelvis.

The difference in the kinematics between the standing and the walking position is the timing of the head to windshield contact. For the standing position, the head contacts the windshield for the speed higher or equal to 30 km/h, while for the walking position it contacts at speeds higher or equal to 40 km/h. Therefore, the Head Injury Criteria (HIC) is different for both positions as presented in Figure 4-30. In the walking position, the dummy is bent and lifted up more, which results in the delay of the head contacting the windshield. The hand and elbow contacts with the hood at 50 and 100 ms are similar to those of the PMHS tests performed by Yang (2000).This contact will reduce the head velocity before contacting the windshield.

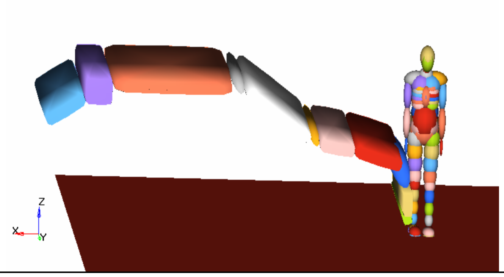
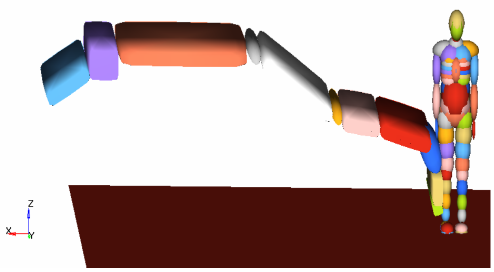
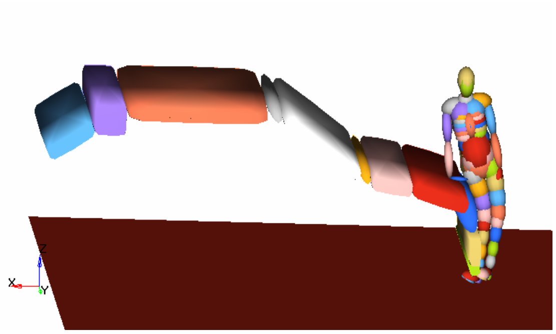
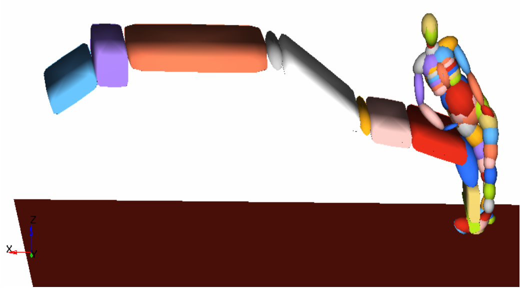
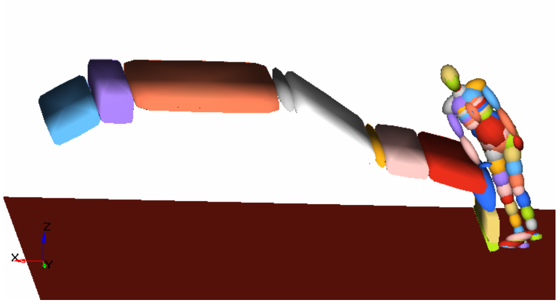
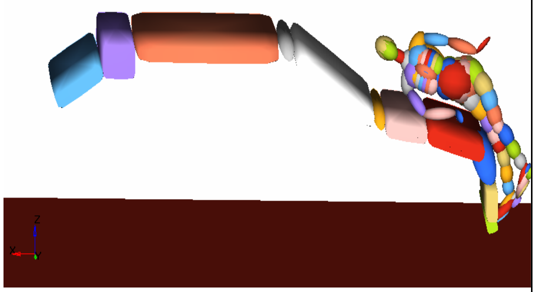
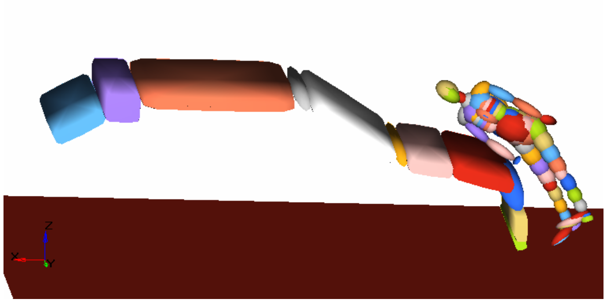
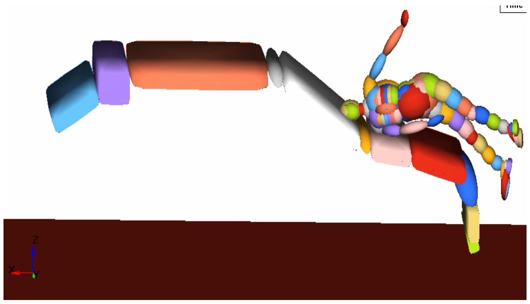
20 km/h	**40km/h**
0ms 	0 ms 
50 ms 	50 ms 
100 ms 	100 ms 
150ms 	150 ms 

Figure 4-28: Kinematics of the Mid-size Male Pedestrian Model (20 km/h & 40 km/h)

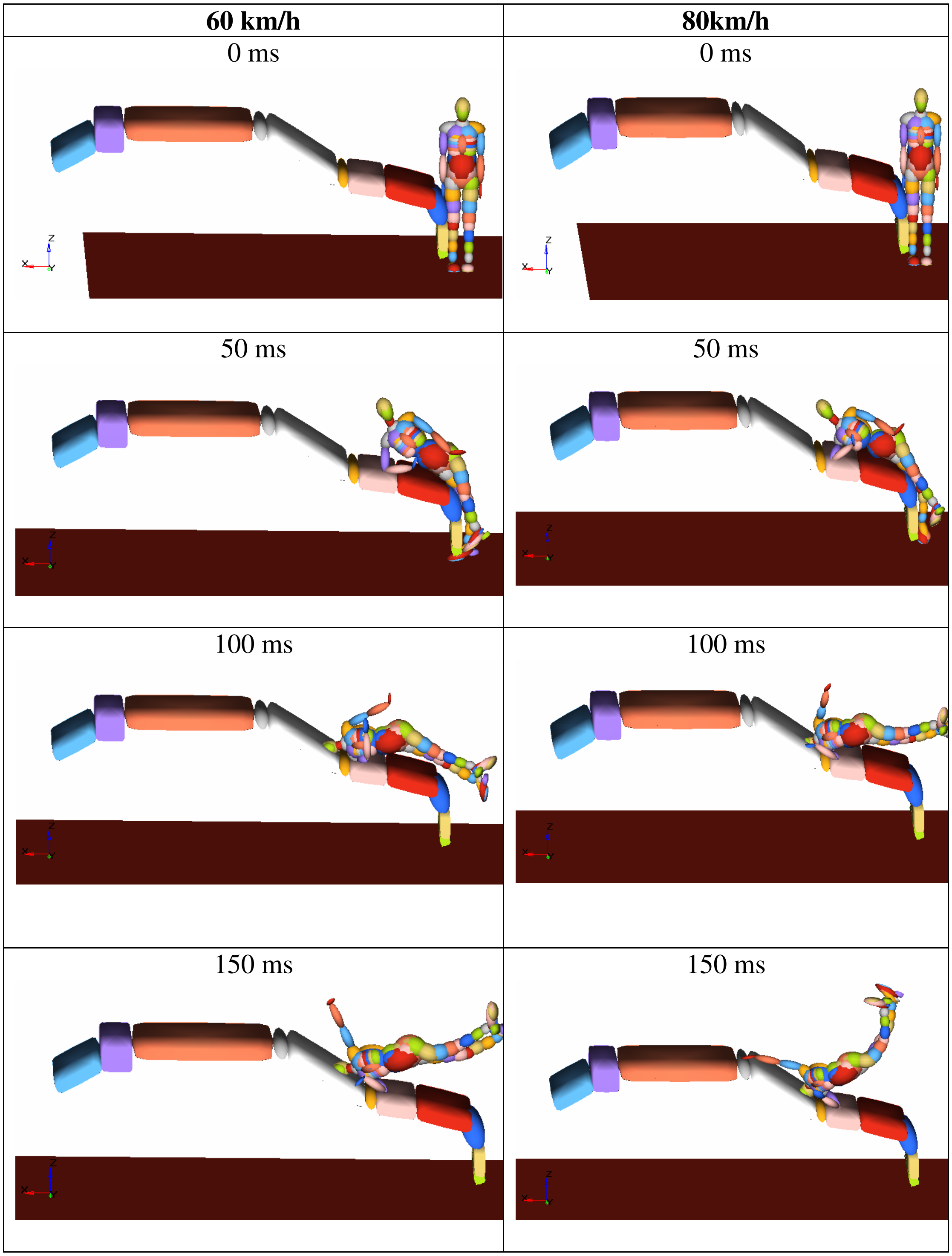


Figure 4-29: Kinematics of the Mid-size Male Pedestrian Model (60 km/h & 80 km/h)

4.3.5 Injury Criteria and Risk Functions for the Mid-size Male Model

The Head Injury Criteria (HIC) is measured for the head contact with the vehicle. Figure 4-30 shows the HIC values for the different impact speeds and for the two dummy positions.

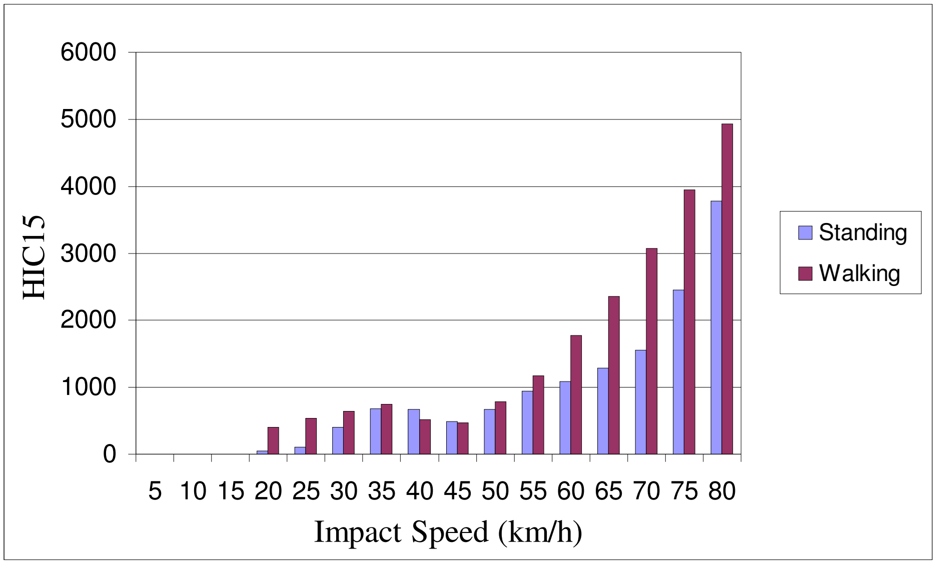


Figure 4-30: HIC15 for the Mid-size Male Pedestrian Model at Different Impact Speeds

NHTSA's head AIS3+ risk function presented in Figure 4-31 is used to correlate the impact speed and the risk of head AIS3 + as presented in Figure 4-32.

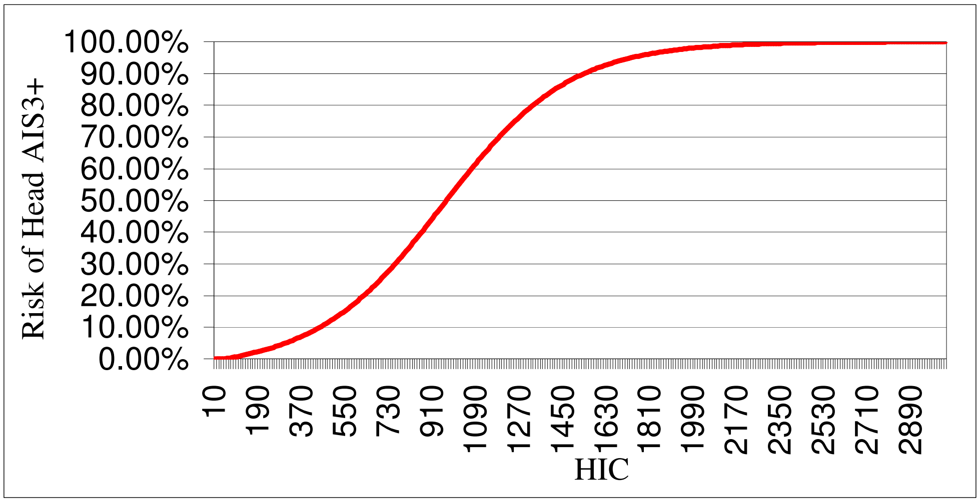


Figure 4-31: Head AIS3+ Risk Function (NHTSA)

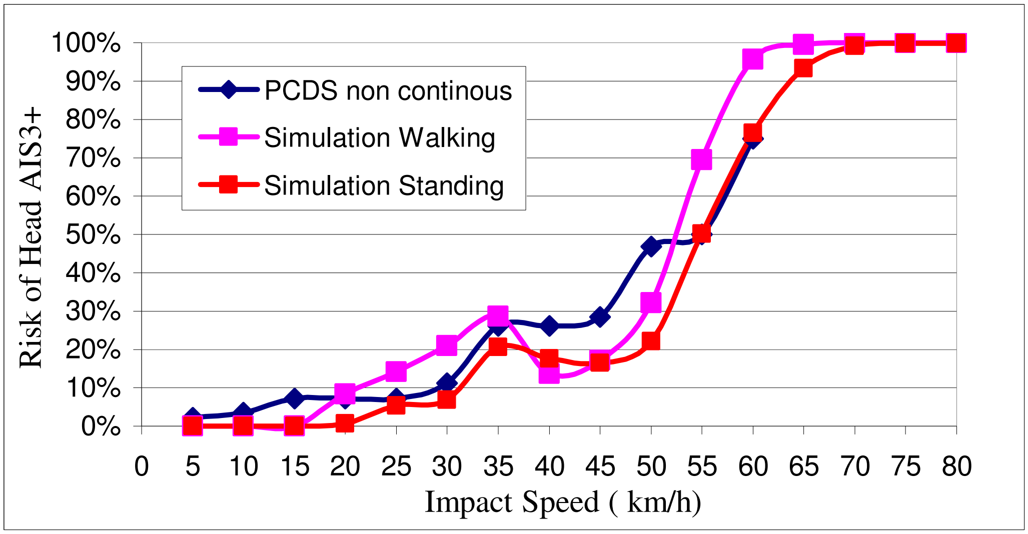


Figure 4-32: Head AIS3+ Risk Functions for the Mid-Size Male and Passenger Car

The simulations show a slight decrease in the risk of head AIS3+ after 35 km/h. This is due to the start of the contact between the head and the windshield, which is less stiff than the hood area. The risk of head AIS3+ is almost the same for the impact speeds of 40 and 45 km/h, despite the fact that for both speeds the head is contacting the windshield and one would expect a higher risk for the 45 km/h impact speed compared to the 40 km/h. The peak head resultant acceleration is the same for both speeds and that explains the similarity in the HIC values.

The simulations also show an “exponential” increase in the risk of head AIS3+ between 45 and 55 km/h. Head resultant acceleration for both impact speeds is compared in Figure 4-33. There are two sequential peaks in the head resultant acceleration, the latter being lower but at wider window time. There is minimal difference in the first peaks, which is the maximum head acceleration for 50 and 55 km/h (around 150 g’s), but the second peak differs between the two impact speeds, 110 g’s for the 55 km/h and 83 g’s for the 50 km/h impact simulation.

The "exponential" increase in the risk of head serious injuries between 45 and 55km/h is observed in both simulations and the PCDS data, which validates previous assumptions that the risk of pedestrian fatality increases exponentially between 30 and 55 km/h.

To summarize, the trend in the risk of pedestrian AIS3+ head injury is similar between the PCDS database and the MADYMNO simulations. There are two "exponential" increases in the risk separated by a constant risk area, the first being between 30 and 35 km/h and the second between 45 and 55 km/h and the constant risk area is between 35 and 45 km/h. This result is one of the core findings of the research.

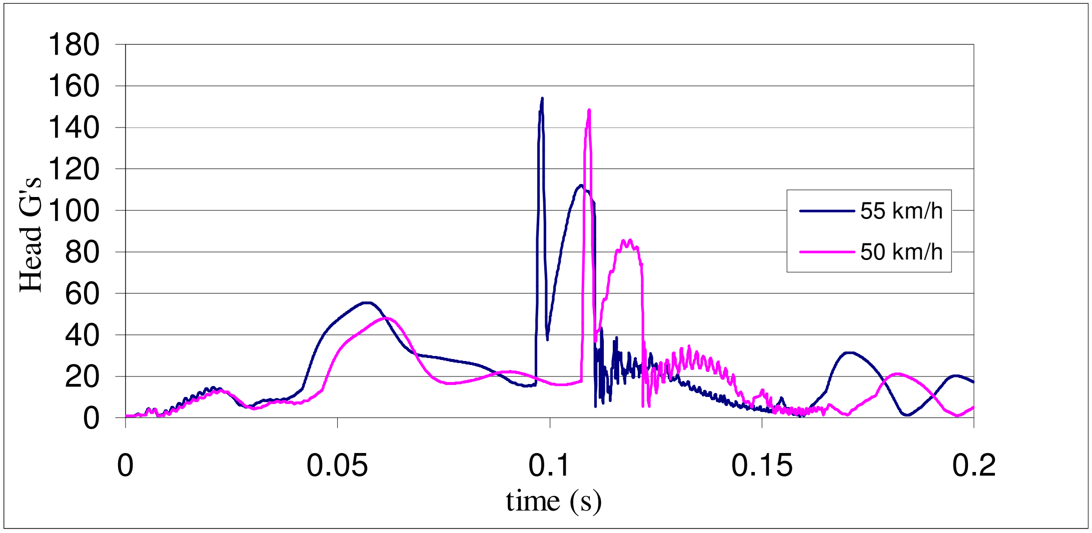


Figure 4-33: Head Resultant Acceleration for 50 and 55 km/h Impact Speeds

4.3.6 Injury Criteria and Risk Function for the 6-Year Old Child

The 6-year old child dummy is positioned facing the front of the vehicle. The 3 ms clip values of the torso's resultant acceleration is used to predict the risk of chest AIS3+. The frontal impact injury criteria as developed by Eppinger *et al.* (1999) for NHTSA are used to correlate the impact speed and the risk of chest AIS3+. The results are presented in Table 4-8 and Figure 4-34.

The risk of chest AIS3+ increases from 47% to 94% between the impact speed of 30 and 50 km/h, which suggests that the reduction of the speed where children are present (residential and school areas) to about 30 km/h would be beneficial.

Table 4-8: Chest Acceleration for the 6-Year Old Child Dummy

Impact Speed (km/h)	3ms Clip for Chest Acceleration (g's)
5	1.4
10	4.8
15	10.3
20	16.8
25	22.4
30	32.1
35	42.9
40	57.0
45	68.3
50	80.3
55	95.2
60	105.4
65	120.3
70	138.2
75	150.4
80	166.0

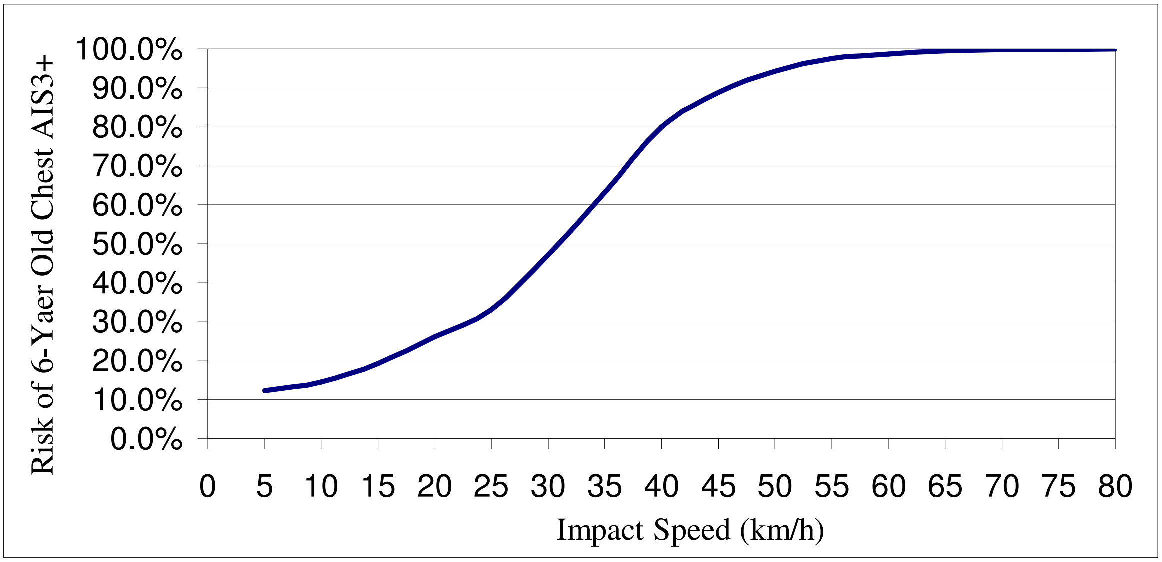


Figure 4-34: Chest AIS3+ Injury Risk Function for the 6-Year Old Child

4.4 Speed Protection Factors

The purpose of this section is to develop speed protection factors that represent the risk of a pedestrian being fatally injured when impacted by a vehicle.

Noting that the PCDS data is not suitable for fatal risk analysis due to the small sample of fatal cases within the PCDS database, a logistic regression is performed to derive the risk of fatality with respect to impact speed and by vehicle type (Figure 4-35).

Based on the PCDS data analysis and on the simulations, it can be concluded that 80 km/h impact speed represents a 100% risk of fatality for pedestrians (Figures 4-5, 4-7, 4-32, 4-34 and 4-35). A protection factor of 1 will be assigned to 80 km/h and other speeds will be assigned a protection factor which is between 0 and 1, representing the risk of a pedestrian being fatally injured at that speed. Table 4-9 shows the risk factors for pedestrian fatal injury with respect to speed limit, with all things being equal, those factors are derived from Figure 4-35.

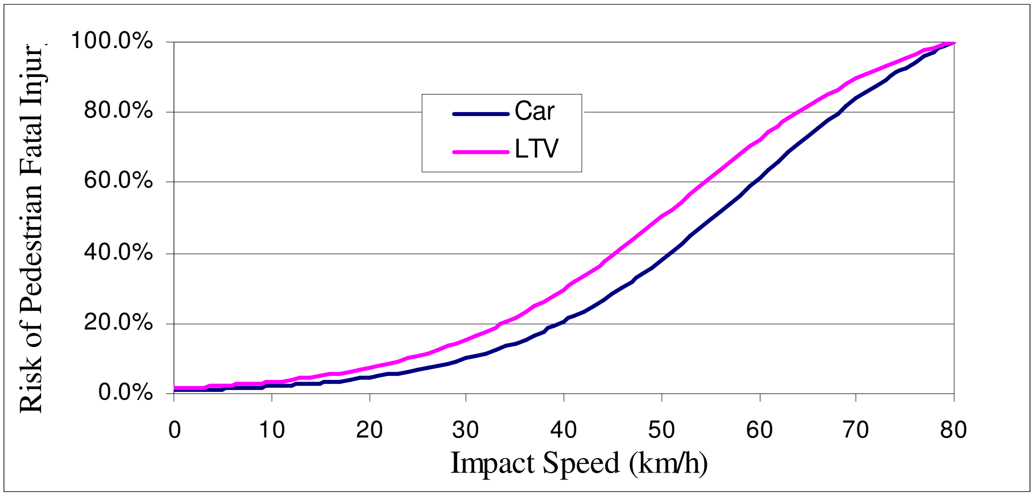


Figure 4-35: Pedestrian Fatality Risk by Vehicle Type

The risk of being fatally injured when struck by an LTV is higher compared with passenger cars. Therefore, it is important to adjust these risk factors where light trucks are more frequent and represent more than 33% (LTV mix in PCDS) of the national vehicle fleet and for areas where children and older people are present.

Table 4-9: Speed Protection Factors by Vehicle Type

Speed Limit	Protection Factor (Passenger Cars)	Protection Factor (LTVs)
30	0.10	0.15
40	0.20	0.30
50	0.38	0.50
60	0.61	0.72
70	0.84	0.90
80	1	1
90	1	1
100	1	1
110	1	1
120	1	1

4.5 Countermeasure for Pedestrian Head Protection

The PCDS data analysis, as well as the simulations, clearly shows that a pedestrian can sustain a serious injury from the head contacting the windshield. The second impact with either the vehicle compartment or the ground will cause serious injuries but it is important to offer a protection for the head while contacting the windshield.

Reducing the stiffness of the windshield will improve the outcome of the head injury. This can be done by using different materials for the windshield and changing glass properties to make it safer during impact. Another solution will be the addition of a curtain air bag that can absorb some energy before the head contacts the windshield. This solution is the countermeasure that is assessed by using simulations.

A 10 cm air bag is positioned parallel to the windshield (Figure 4-37 and 4-38), the contact characteristics of which are presented in Figure 4-36. The stiffness of the bag is a typical loading value for a regular air bag, which is around 52 KN/m as derived from finite element simulations of an air bag. The unloading of the bag happens when the head reaches the middle of the bag.

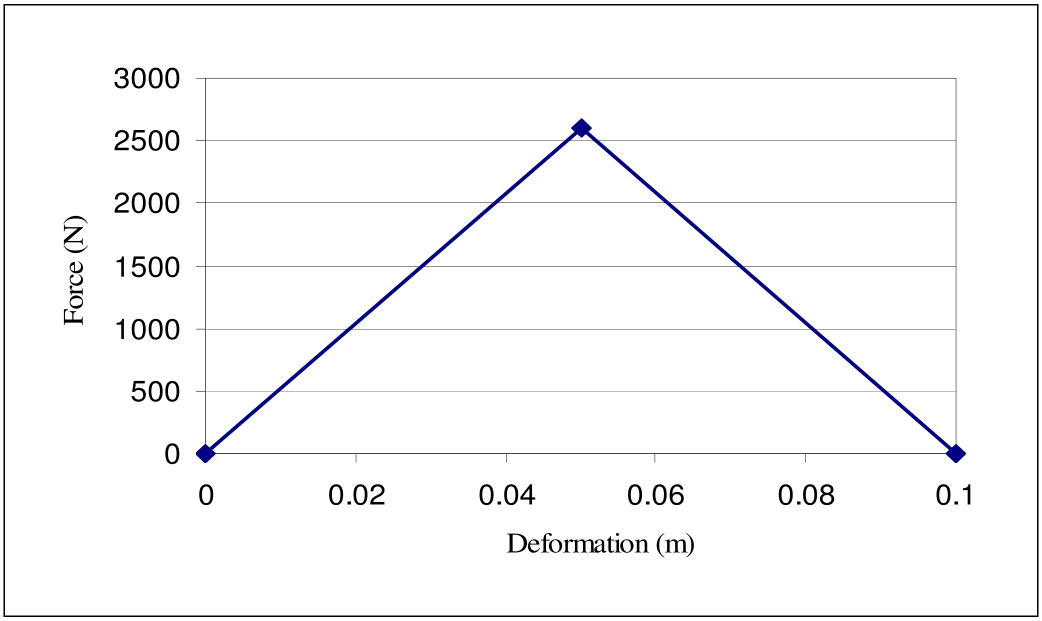


Figure 4-36: Air Bag Stiffness for Pedestrian Head Protection

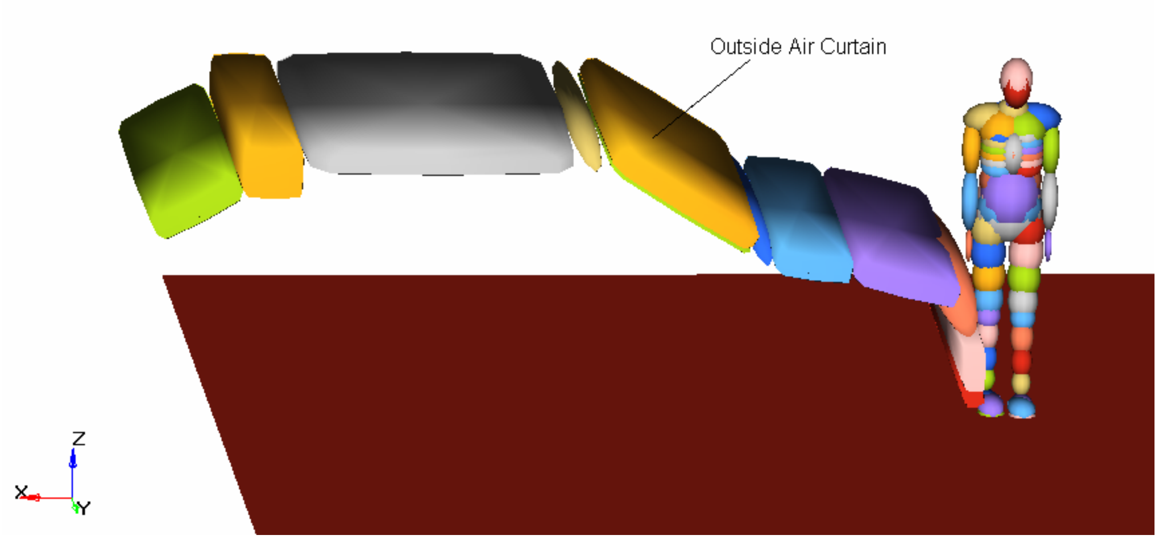


Figure 4-37: Model of an Outside Air Curtain for Pedestrian Head Protection

Figure 4-38: Outside Air Curtain for Pedestrian Head Protection

The outside air curtain has a relatively good effect in reducing the injuries to the head by lowering the HIC as presented in Table 4-10.

Table 4-10: Risk of Head AIS3+ With and Without the Outside Air Curtain

Impact Speed (km/h)	HIC (w/o)	Risk of Head AIS3+ (%) (w/o)	Effectiveness (%)
40	514/543	13.7/12.8	7
45	467/487	11.2/12.1	-8
50	780/667	32.2/23.2	28
55	1176/724	69.5/27.5	60
60	1773/1056	95.6/67.4	30

The air bag was most effective for the impact speed of 55 km/h. There was a 60% reduction in the head AIS3+ risk. Above 60 km/h, the air bag is effective but it is unable to decrease the HIC below 1000, which is the head tolerance to impact load and responses that correspond to a 50% risk of head AIS3+.

This countermeasure is designed for head protection with windshield impact. Therefore, it does not offer any protection for the head contacting the hood. The rover 25 is a small passenger car with low hood edge height and small hood area so the head will impact the windshield at lower speeds than it does for big passenger cars and light trucks. For the latter vehicle, head protection needs to be offered for the hood contact rather than the windshield. Adjusting the geometry and the stiffness of the hood will help reducing the head injuries from the hood contact.

CHAPTER 5

INFRASTRUCTURE SAFETY RATING FOR PEDESTRIANS

5.1 Road Protection and Prevention Score

Star rating a road is a proactive approach to road safety. It enables sections of road with a relatively high level of risk to be identified before a crash occurs.

The degree of risk, or just how safe a road is, depends to an extent on whether safety has been built-in to it through the inclusion of design elements such as wide lanes and shoulders and safety barriers, which are known to have an impact on the likelihood of a crash and its severity.

Star rating is based on inspection of these various design elements and rating the impact which they have on the likelihood of a crash and its severity. This approach to road safety assessment is increasingly being taken up internationally. Similar types of road inspection programs are now undertaken by the European Road Assessment Program EuroRAP in countries such as Sweden, Germany, Austria, Britain, Iceland, Netherlands, Spain and Switzerland. In many countries, the star rating process is driving the development of innovative engineering for safer roads.

At the heart of Star Rating is the Road Protection and Prevention Score (RPPS) which is presented in Equations 5.1 to 5.3.

$$\text{Along RPPS} = \text{Likelihood Factor} \times \text{Protection Factor} \qquad (5.1)$$

$$\text{Crossing RPPS} = \text{Likelihood Factor} \times \text{Protection Factor} \qquad (5.2)$$

$$\text{Total RPPS} = \text{Along RPPS} * \text{Crash Type Factor} + \text{Crossing RPPS} * \text{Crash Type Factor} \quad (5.3)$$

Likelihood and protection factors for both types of pedestrian crashes are derived in previous chapters. Crash type factor is the weighting factor for each type of pedestrian crashes. Data from several countries have lead to the conclusion that 20% of pedestrian fatal crashes happen while pedestrians are walking along the road while 80% happen while pedestrians are crossing the road. The crash type factor will be 0.2 for along the road crashes and 0.8 from crashes while crossing the road. These crash type factors can be country specific and are derived where pedestrian fatalities are broken down by type of crash (along vs. crossing).

Road Protection and Prevention Scores (RPPS) bands are defined to derive a Star Rating system (1 to 5 Stars) based on the RPPS score for each type of pedestrian crashes and the respective crash type factor. Pre-defined road characteristics for each Star Rating (1 to 5 Stars) is defined based on engineering judgment then an RPPS interval for each Star will be derived using the model developed previously, that interval will consist the RPPS Band for each Star Rating (Table5-1).

A 5-Star road for pedestrians will be a road where pedestrian facilities are physically separated form the main road carriageway with signalized crossing available where pedestrian wish to cross. The Speed should be limited to less than 40 km/h. This Road will have an RPPS varying between 0 and 0.27; therefore the RPPS band for a 5-Star road is defined to be between 0 and 0.27.

A 1-Star road for pedestrians will be a multilane road with no crossing facilities and no sidewalks for pedestrian to use and the speed limit on this road is higher than 60 km/h. This road will have an RPPS varying between 6.00 and 52.16; therefore the RPPS band for a 1 –Star road is defined to be between 6.00 and 52.16.

This Star Rating system will help to compensate for any subjective decision made while deriving the Likelihood and Protection factors. In other word, the pre-defined road characteristics for each of the 5 Stars will be used as the criteria for setting up RPPS bands for Star Rating.

Table 5-1: Star Rating Bands for Pedestrian RPPS

	Total	Along	Crossing
5 Stars	0.00-0.27	0.00-0.06	0.00-0.32
4 Stars	0.27-0.54	0.06-0.16	0.32-0.64
3 Stars	0.54-2.72	0.16-0.80	0.64-3.20
2 Stars	2.72-6.00	0.80-1.20	3.20-7.20
1 Stars	6.00-52.16	1.20-4.80	7.20-64.0

A road section of 4 lanes to cross, with no median or crossing facilities and no sidewalks with speed limit of 50 km/h is a high risk road both for likelihood and protection and the RPS for this road is 2.94 which correspond to 2 stars.

5.2 Safety Rating of a Route

Typically a road protection score is computed for each 100 m long section. The RPPS for a route is presented in Equation 5.4.

$$\text{Route RPPS} = \sum \text{100 m section RPS} \,/\, \text{number of 100 m sections} \qquad (5.4)$$

Aggregation of the 100 m sections is done for a total length of x km where similarity in infrastructure is observed, with only difference the existence or not of pedestrian crossings in each 100 m section. Typically the aggregation of 100 m sections is done by length of 1, 2 or 3 km or by a predefined section of road with uniform infrastructure features.

5.3 Safety Rating Maps

A color coded map is used to present the Safety Rating of a network. Figure 5-1 shows an example of a Safety Rating map for pedestrians in Costa Rica.

The 5-Stars green links represent road sections with a speed limit less than 50 km/h and a separation between pedestrians and motorized vehicle is provided and the intersections are signalized. This type of risk mapping will enable decision makers to target low ratings links, the 1-Star and 2-Stars links (black and red), design engineering programs for those links and upgrade their safety to a 4-Stars or 5-Stars rating. Similar rating and improvement process is driving the vehicle manufactures to improve the passive safety of their vehicles and score high ratings in various Car Assessment Programs (per ex. US NCAP).

Such infrastructure safety management process that focuses on the overall safety of the network is a better tool for decision making and investment prioritization to improve the safety of the national network than following a traditional black-spot approach for which reliable crash data is not available for developing countries.

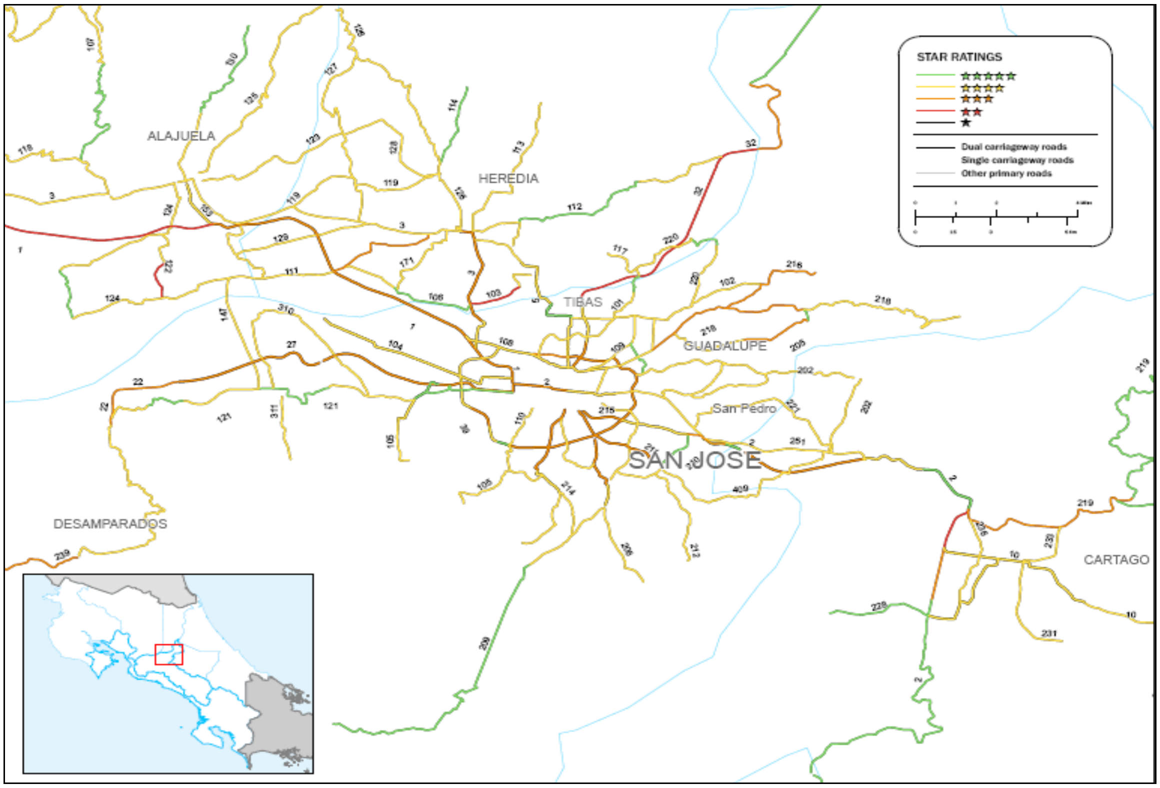


Figure 5-1: Pedestrian Star Rating in Costa Rica

5.4 Sensitivity Analysis of the Star Rating in Urban/Semi Urban Environment

The purpose of the sensitivity analysis performed on the RPPS is the check how sensible the Star Rating model is for various road design features and speed.

The rating is most sensitive to the separation between pedestrians and motor vehicles and to speed limit, which is aligned with the Vision's Zero philosophy of "Separation and Integration" between pedestrians and motor vehicles (Appendix B).

Reduction in risk is not observed for roads where only a sidewalk is offered without any physical separation

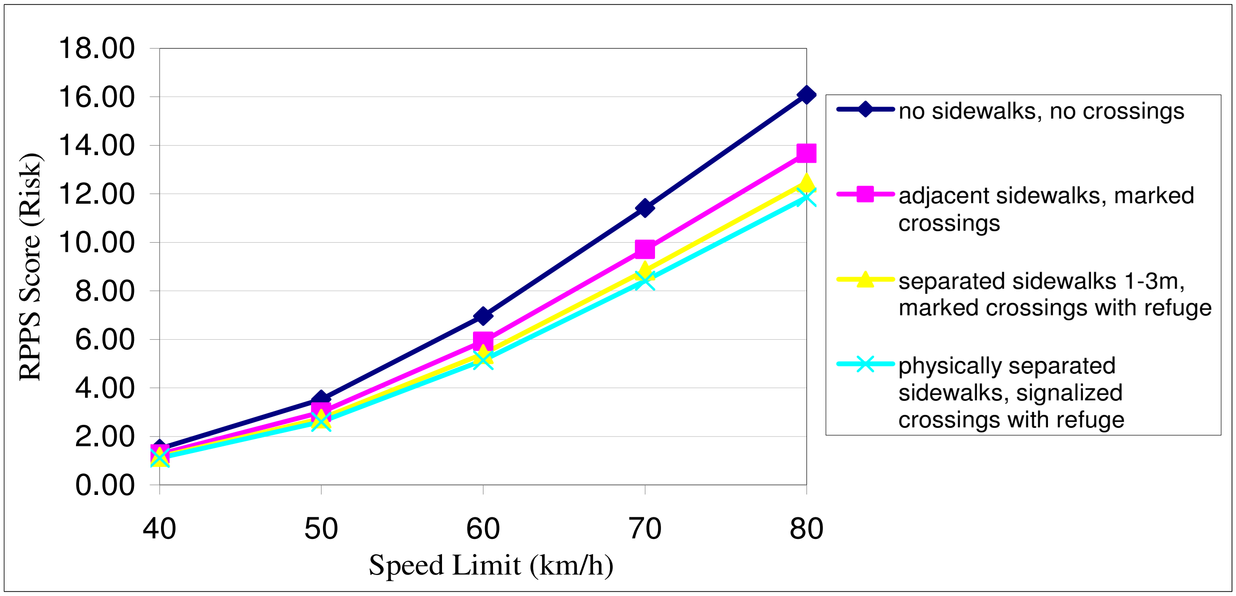


Figure 5-2: RPPS for Pedestrians Crossing in Urban Environment

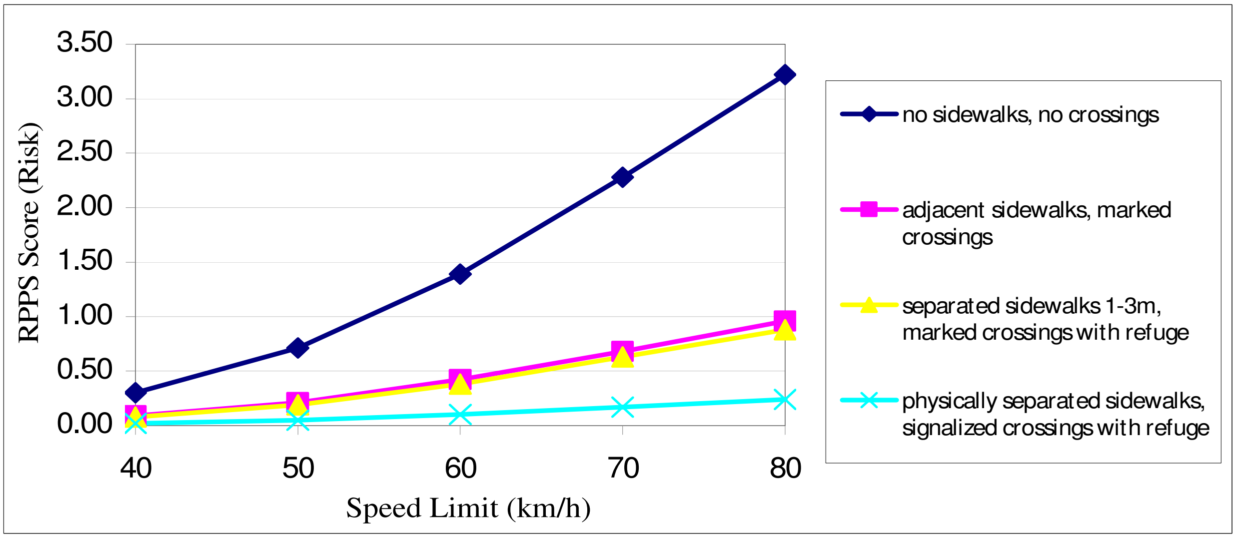


Figure 5-3: RPPS for Pedestrians Walking Along the Road in Urban Environment

5.5 Casualty Prediction Model for Pedestrians

The Road Protection and Prevention Score is converted to a casualty prediction model to estimate the contribution of the road design to pedestrian fatalities to be able to quantify the benefit of engineering programs on safety. This conversion is done by multiplying the RPPS by a country specific factor for each crash type that will transform this unite less risk number (RPPS) to a casualty rate (fatality per 100 million veh-km) which is converted to a density measure (fatality/km) by multiplying the later by the vehicular traffic flow and a pedestrian exposure factor.

Same RPPS may lead to different casualty estimation in different countries and this is represented by the introduction of a country specific factor. It is believed that such country factor will capture different road user behavior and other factors between countries.

$$\text{PFA} = \text{Along RPS} * \text{Country Factor Along} * \text{Exposure Factor} * \text{Traffic Flow} \tag{5.5}$$

$$\text{PFC} = \text{Crossing RPS} * \text{Country Factor Crossing} * \text{Exposure Factor} * \text{Traffic Flow} \tag{5.6}$$

$$\text{PFT} = \text{Pedestrian Along Fatalities/km} + \text{Pedestrian Crossing Fatalities/km} \tag{5.7}$$

where:

PFA – Pedestrian Fatalities per km while walking along the road

PFC – Pedestrian Fatalities per km while crossing the road

PFT – Total number of Pedestrian Fatalities per km

The exposure factor represents the effect of pedestrian flow on casualties all things being equal. A typical crash prediction model (Turner *et al.,* 2006) takes the form of product of power functions as presented in equation 5.8.

$$A = \alpha Q^{\beta 1} P^{\beta 2} \tag{5.8}$$

A - Number of crashes per year

Q - Vehicle traffic flow

P - Pedestrian traffic flow

Turner *et al.* (2005, 2006) derived the exponents of equation 5.8 for a number of crashes in New Zealand. The exponent for the pedestrian flow (β_2) is around 0.4. This result is similar to the findings in UK studies.

Pedestrian flow is categorized as low, medium and high according to the banding in Table 5.2. An exposure factor of 1 assigned to medium pedestrian flow, relative risks are derived for the medium and high flows based on the value of 0.4 for the exponent of pedestrian flow in equation 5.8.

Table 5-2: Pedestrian Flow Categories

Flow Category	Pedestrian Flow Range (Ped/Day)
Low	0-2000
Medium- Low	2000-4000
Medium	4000-6000
Medium-High	6000-8000
High	>8000

The exposure factor for each pedestrian flow category is shown in Equation 5.9:

$$Exposure\ \ Factor\ \ of\ \ Category\ \ i = [\frac{(Average\ \ Pedestrian\ \ Flow\ \ of\ \ Category\ \ i)}{5000}]^{0.4} \quad (5.9)$$

where i is the pedestrian flow category other than medium

The average pedestrian flow for the medium category is assumed to be 5000 Pedestrian per day.

According to the flow range for each category as specified in Table 5-2 and using equation (5.9) for a constant vehicular flow, an exposure factor for each flow category is derived relatively to the medium flow category whose exposure factor is 1 (Table 5-3).

Table 5-3: Pedestrian Exposure Factor

Pedestrian Flow Category	Exposure Factor
Low	0.5
Medium-Low	0.8
Medium	1.0
Medium-High	1.2
High	1.7

5.5.1 China Country Fatality Factor

Infrastructure and pedestrian fatality data are required to derive the country fatality factor. Official statistics for the Chinese Ministry of Public Security (MPS), show that pedestrian and cyclists fatalities account for more than 60% of the total number of crash related fatalities. Infrastructure data was available also and could be linked to fatality data. For these reasons, China is the country chosen to estimate its Fatality Factor.

Road Protection and Prevention Score (RPPS) is calculated for a sample of sections in urban areas with medium pedestrian flow (4000-6000 pedestrian per day) in Liaoning province in China as part a World Bank financed project. Data on pedestrian fatalities for a period of 3 years as well as the traffic and pedestrian flow are collected.

The dataset used consist of 17 different roads in urban environment as described in Table 5-4. Linear regression between the fatality rate and the RPPS does not seem reasonable from Figure 5-4, but the aim from the regression is to be able to identify the contribution of the infrastructure to the number of pedestrian fatalities. In other word, how much the quality of the infrastructure is contributing to the number of the fatalities all things (behavior, vehicle type) being equal.

The regression equation shows that around 46 % of the variation in the pedestrian fatality can be explained by the variation in the RPPS score (R^2=0.46), the rest will be explained by other factors like behavior and traffic mix. A regression equation passing by the origin determines the country factor for China that correlated the fatality rate and RPS for pedestrians, this factor is equal to 2.

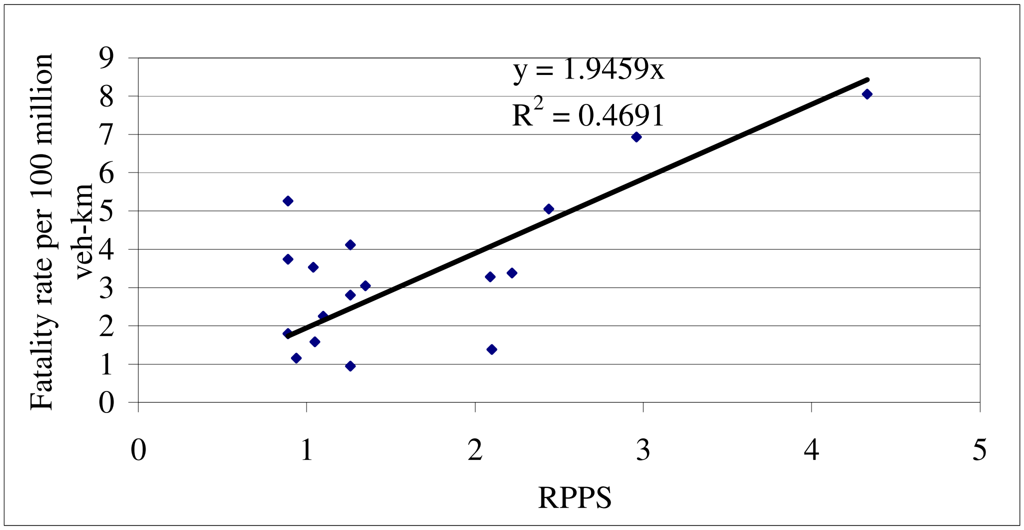


Figure 5-4: Correlation between RPPS and Fatality Rate for Pedestrians

Table 5-4: Road Used to Derive China Fatality Factor

Name	Length (km)	Daily Pedestrian Flow (Ped/Day)	Daily Vehicle Flow (Veh/Day)	Number of Lanes	Sidewalk Provision	Crossing Facilities
Dongming Road	1.6	1512	1406	4	Non-physical separation	Unsignalised unmarked without refuge
Shengli Road	2.9	1782	1844	4	Non-physical separation	Unsignalised unmarked without refuge
Yuming Road	5.2	1598	1275	4	Non-physical separation	Unsignalised unmarked without refuge
Xinglong Street	7.4	12708	1950	6	Non-physical separation	4-leg Signalized without Refuge
Qingnian Street	1.2	13624	22776	4	Non-physical separation	Unsignalised unmarked without refuge

CHAPTER 6

CRASHWORTHINESS EVALUATION OF MOTORIZED/NON-MOTORIZED VEHICLE LANES SEPARATORS

6.1 Introduction

Road traffic safety has become a top health concern in China. Official statistics from the China Ministry of Public Security (MPS) indicate that the average number of deaths per 10,000 vehicles from 2001 to 2005 was 11.4, which is several times greater than the U.S. (1.6), Germany (1.3), Japan (0.9), and Malaysia (4.2), making China one of the world leaders in traffic deaths and injuries. Road crashes kill more Chinese people aged one to 34 years than all other causes of death combined. Affected most by this public heath crisis are young people (aged 21 to 40), who make up 46% of road crash deaths and 60% of injuries; men, who account for 75% of all those injured and killed in road crashes; and vulnerable road users (VRUs, meaning pedestrians, motorcyclists and bicyclists), who account for 60% of road crash deaths and injuries. Despite significant achievements by the government in reducing the number of accidents over the past five years, the percentage of fatal accidents has increased.

As part of the $218 million Bank Financed Transport Project in Liaoning Medium Cities, a Traffic Safety and Traffic Management Component ($22.18 million) has been designed to improve the traffic flow and the safety in the project cities.

This component is designed to address the concerns raised by the public according to the extensive public participation process that was conducted in all project cities. It was also designed to help the implementation of the newly passed National Road Safety Law that incorporated the "People First Initiative". One of the concerns raised by the public is to provide a physical separation between Motorized and Non-motorized (NMV) traffic to provide a mobile and safe transport network for the NMV road users. The project is financing the installation of lane separators in Benxi, Fushun, Jinzhou, and Panjin.

There are no national or international guidelines or standards that regulate the crashworthiness and the use of such physical separators. Therefore, a study is needed to assess the crashworthiness of the separators currently being used within the Liaoning Medium Cities Infrastructure Project and other World Bank Financed projects in China and East Asian Region to optimize the benefit of such separators.

The primary objective of this chapter is to assist The World Bank in evaluating the crashworthiness of two lane separators for motorized and non-motorized traffic developed for the cities of Fushun and Jinzhou in China.

6.2 Vehicle Finite Element Model Selection and Update

A vehicle finite element model representing a 2001 Ford Taurus (Figure 6-1) was selected for use throughout this study. The 2001 Ford Taurus is a full-size car sedan available in front wheel drive. The model was developed at the Federal Highway Administration National Crash Analysis Center (FHWA/NHTSA) at the George Washington University and is available from their web site. Several modifications were made to the model to make it suitable for the type of impact performed in this study.

The Taurus FE model, shown in Figure 2, consists of 778 parts, 882,225 nodes, 784,259 shell elements, 4 beam elements, and 66,523 solid elements. Before the model was used in the simulations, several checks and modifications were performed to ensure that it is applicable for the type of impacts used in this study. The mass distribution was checked, and rotating (spinning) tires were incorporated in the model. The spinning of tires affects the lift of the vehicle upon impact with the separator base. Furthermore, dynamic relaxation simulations were performed to ensure that the vehicle was at equilibrium under gravity loading.

The vehicle's Gross Vehicle Weight Rating (GVWR), which is the maximum allowable total loaded vehicle weight, is 2,120 kg. The FE model weight was set at 1,655 kg, representing the unloaded vehicle weight with two passengers at 78 kg each. Table 4-1 shows a summary of the vehicle's specifications, while Table 4-2 shows the FE model information.

Figure 6-1: 2001 Ford Taurus

Table 6-1: 2001 Ford Taurus Specifications

Weight	1655kg
Engine Type	3.0L V6
Tire Size	P215/60R 16
Attitude	F – 705 mm R – 672 mm
Wheelbase	2755 mm
CG Rearward of front wheel C/L	1035 mm
Model Year	2001

Figure 6-2: 2001 Ford Taurus FE model

Table 6-2: Taurus FE Model Information

Number of Parts	778
Number of Nodes	882,225
Number of Shells	784,259
Number of Beams	4
Number of Solids	66,523
Total Number of Elements	855,379

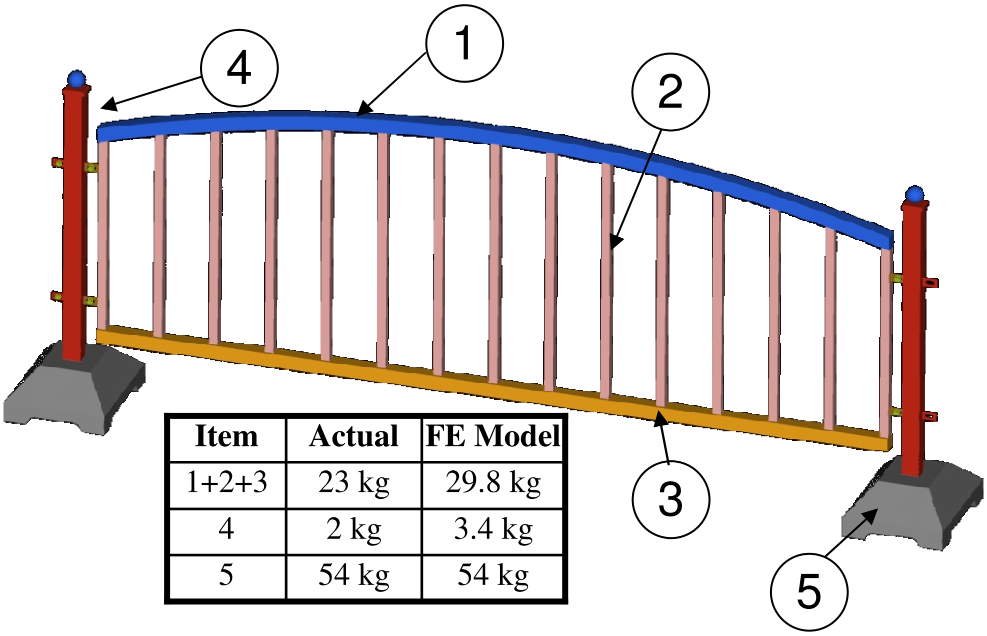
6.3 Lane Separators Finite Element Model Development

The focus of this study was on two lane separators developed for the cities of Jinzhou and Fushun in China. The lane separators are designed to provide a physical separation between motorized and non-motorized traffic for a mobile and safe transport network for road users. The following sections describe the Finite Element (FE) model development of the lane separators.

6.3.1 Jinzhou Separator

The Jinzhou separator is tubular structure that connects, using two M10 bolts and nuts, to a standalone post with a cast iron base (Figure 6-3). The geometry of this lane separator was extracted from design drawings supplied by the Liaoning Urban Construction Project and Renewal Office (LUCRPO). A finite element model of the separator was created based on the extracted geometry. Special care was taken to have accurate representation of the separator geometry to ensure correct mass. Figure 6-4 shows the separator and FE model mass comparison. A fine mesh was used throughout the model to ensure accurate contact behavior and interaction between the vehicle and the separator. A detailed bolt-washer-nut assembly was incorporated in the model (Figure 6-5). This detail significantly improves the behavior of the model at the cost of increased computation time.

Figure 6-3: Jinzhou Separator with Post and Base Detail



Item	Actual	FE Model
1+2+3	23 kg	29.8 kg
4	2 kg	3.4 kg
5	54 kg	54 kg

Figure 6-4: Jinzhou Separator and FE Model Mass Comparison

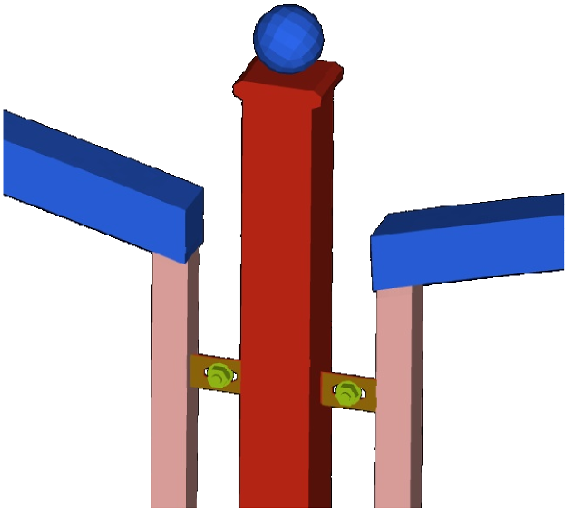


Figure 6-5: M10 connecting bolts and nuts Detailed Model

Fifteen segments of the Jinzhou Separator were linked together to form a complete chain in the impact simulations for a total length of 45 m (Figure 6-6). The two ends of the separator segments were not constrained in the finite element model. The displacements of the first and last segments were monitored to ensure that these displacements are negligible. Table 6-3 shows a summary of the Jinzhou Separator FE model's information 15 segments.

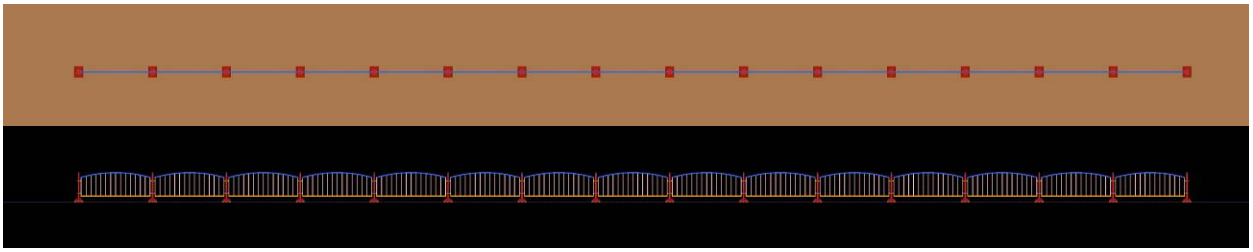


Figure 6-6: Jinzhou Separator FE Simulation Setup

Table 6-3: Jinzhou Separator FE Model Information

Number of Parts	13
Number of Nodes	493,416
Number of Shells	452,195
Number of Beams	64
Number of Solids	33,024
Total Number of Elements	485,282

The LS-DYNA material type 24, Piecewise Linear Isotropic Plasticity, using ASTM A36 steel material property was used for all steel tubing in the model. Table 6-4 and Figure 6-7 show the material data and effective stress vs. effective strain load curve used.

Table 6-4 ASTM A36 Steel Material Properties

Density	7.89 g/cc
Tensile Strength, Yield	270 MPa
Modulus of Elasticity	200 GPa
Poisson's Ration	0.3
Plastic Strain Failure	0.35

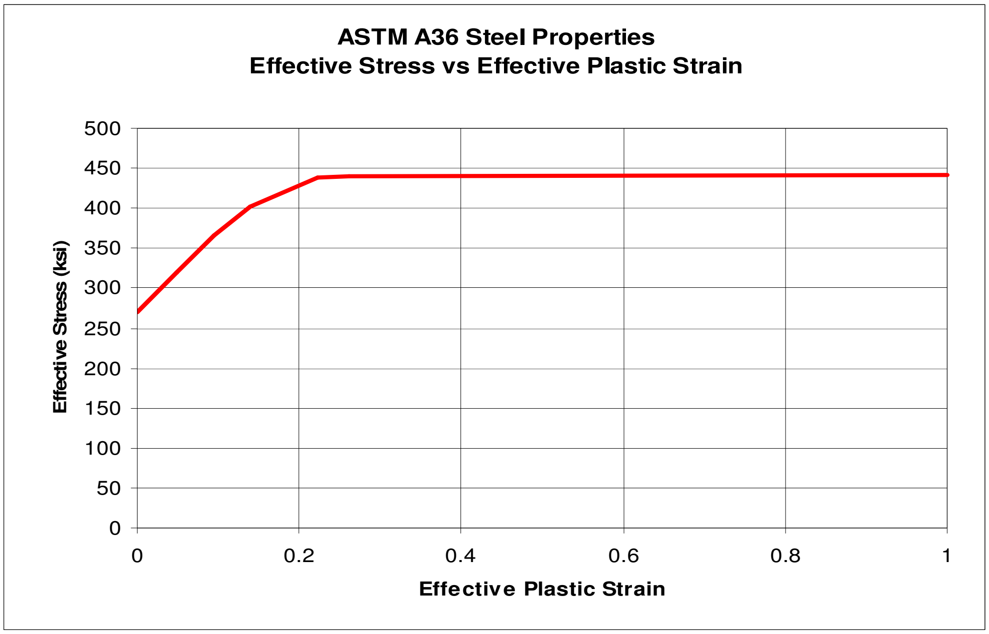


Figure 6-7: ASTM A36 Steel Effective Stress vs. Effective Strain

6.3.2 Fushun Separator

The Fushun Separator is wire mesh-based structure that connects, using two M10 bolts and nuts, to a standalone post with a concrete base (Figure 6-8). The geometry of this lane separator was extracted from design drawings supplied by LUCRPO. A finite element model of the separator was created based on the extracted geometry. Special care was taken to have accurate representation of the separator geometry to ensure correct mass. Figure 6-9 shows the separator and FE model mass comparison. A fine mesh was used throughout the model to ensure accurate contact behavior and interaction between the vehicle and the separator. Similar to the Jinzhou separator, detailed bolt-washer-nut assembly was incorporated in the model.

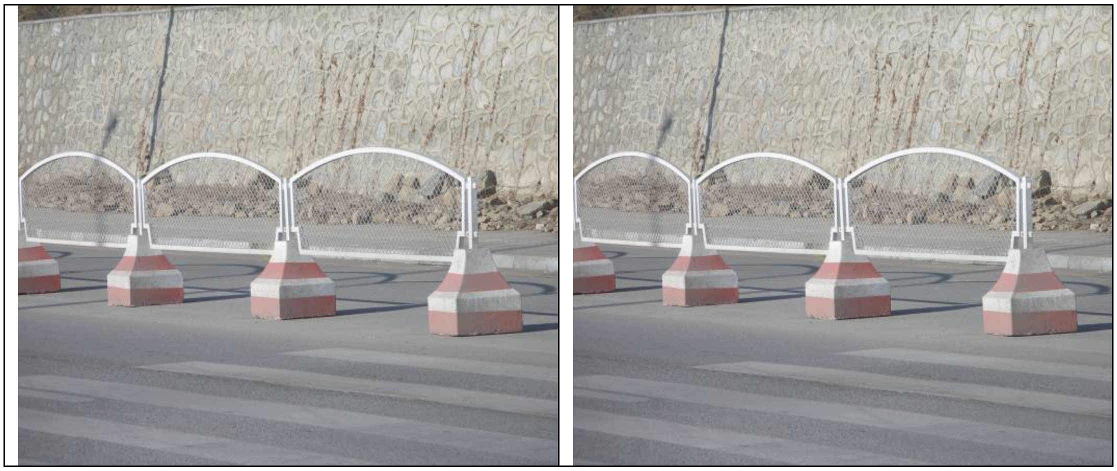
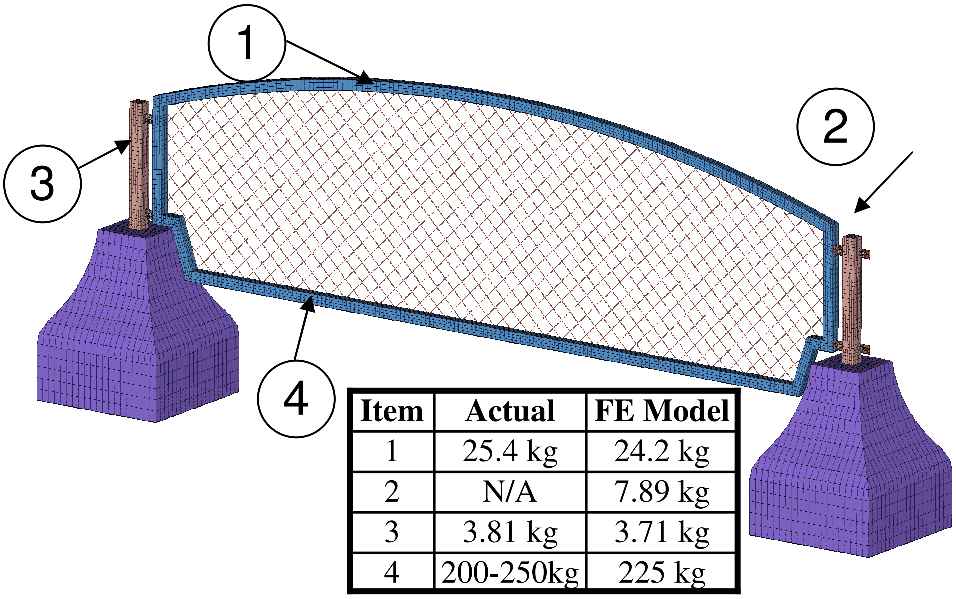


Figure 6-8: Fushun Separator with Post and Concrete Base Detail



Item	Actual	FE Model
1	25.4 kg	24.2 kg
2	N/A	7.89 kg
3	3.81 kg	3.71 kg
4	200-250kg	225 kg

Figure 6-9: Fushun Separator and FE Model Mass Comparison

Fifteen segments of the Fushun separator were linked together to form a complete chain in the impact simulations for a total length of 45 m (Figura 6-10). The two ends of the separator segments were not constrained in the finite element model. The displacements of the first and last segments were monitored to ensure that these displacements are negligible. Table 6-5 shows a summary of the Fushun separator FE model.

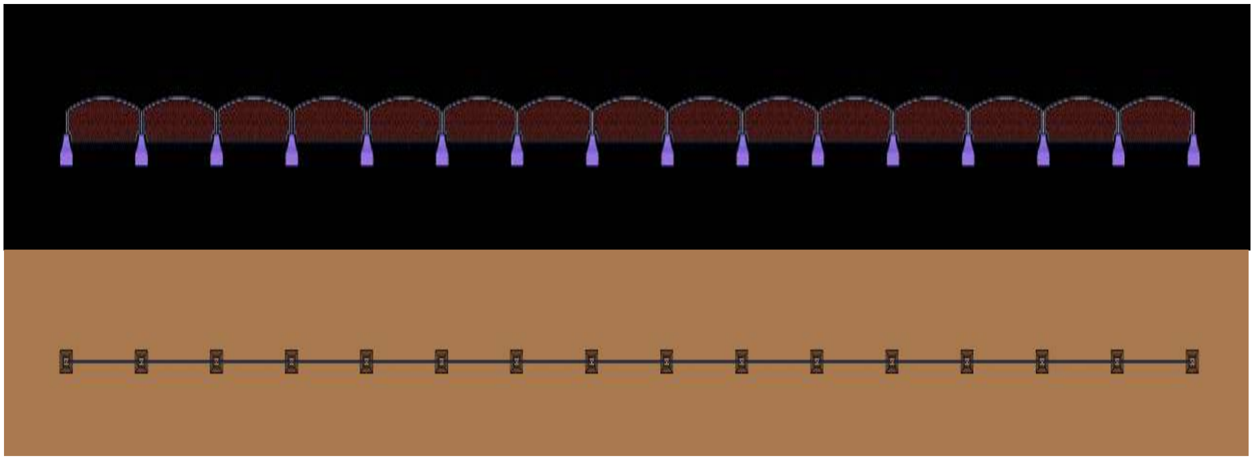


Figure 6-10 Fushun Separator FE Simulation Setup

Table 6.5: Fushun Separator FE Model Information

Number of Parts	11
Number of Nodes	252,414
Number of Shells	131,921
Number of Beams	48,094
Number of Solids	72,768
Total Number of Elements	252,782

Similar to the Jinzhou separator, the Piecewise Linear Isotropic Plasticity material model using ASTM A36 steel property was used for all the steel tubing and wire mesh in the model. Table 6-4 and Figure 6-7 show the material data and effective stress vs. effective strain load curve used in the model. For the concrete base, the Winfrith Concrete material model was used with a density of 2.35 g/cc.

6.4 Impact Simulations

Simulations of the Ford Taurus impacting the lane separators at an angle of 20 degrees and speed of 30 km/h were performed to assess their ability to provide a physical and safe separation between motorized and non-motorized traffic. Each separator FE model was combined with the surrounding paving and Taurus FE model. As previously mentioned, a total of 15 segments of each separator were used for a total length of 45 m. The impact point was between posts 6 and 7 at the center of segment 6 of the separators as shown in Figure 6-11. Appropriate contact definitions were assigned to capture the interactions between the different vehicle and separator components.

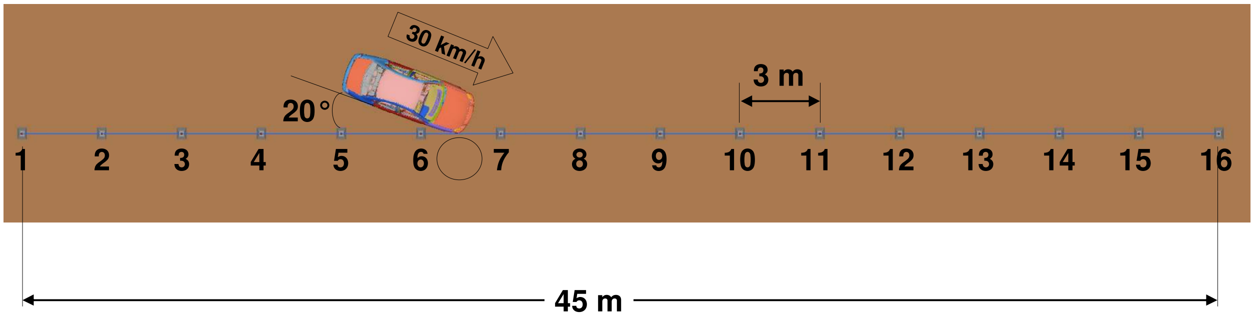


Figure 6-11: Simulation Setup Showing Impact Point for Jinzhou and Fushun Separators

Table 6-6 shows a summary of the initial and boundary conditions for both Jinzhou and Fushun separators.

Table 6-6: Initial and boundary Conditions for Jinzhou and Fushun Separators

Separator Segment Length	3 m
Total Number of Segments	15
Total Separator Length	45 m
Impact Speed	30 km/h
Impact Angle	20 Degrees
Impact Point	Between posts 6 and 7

6.5 Lane Separators Crashworthiness Evaluation

The results from simulations of both Jinzhou and Fushun separators are discussed in this section. Key observations at different stages of the impact are described, evaluations of the lane separators are discussed, and plots of the vehicle longitudinal velocity and separators relative displacements are presented.

6.5.1 Evaluation of Jinzhou Separator

The Ford Taurus, travelling at a constant speed of 30 km/h, impacted the Jinzhou separator at an angle of 20 degrees with the passenger side front bumper corner aligned to the center of segment 6 of the separator between posts 6 and 7 (Figure 6-12). Shortly after impact, the vertical square tubes of the separator yielded and bent slightly at the impact point following the vertical cross sectional shape of the bumper corner. The vehicle continued its trajectory pushing segment 6 of the separator with 2.5 km/h reduction in longitudinal speed. At 0.225 seconds, the bumper contacts post 7, causing it to move laterally and subsequently moving segment 7 of the separator at 0.4 seconds so that it is approximately 40 degrees with respect to the front bumper of the vehicle. From 0.4 seconds to 0.6 seconds, the vehicle pushes segment 7, reducing the impact angle so that the segment is almost perpendicular to the vehicle front and causing a 4.5 km/h reduction in vehicle velocity. At 0.6 seconds, the front center bumper of the vehicle contacts post 8 and continues to push the separator with no reduction in vehicle velocity. Sequences of images from the Jinzhou separator simulation are shown in Figure 6-13 and Figure 6-14.

After 1 second of total simulation time, the vehicle's velocity is slightly reduced from 30 km/h to 21.5 km/h (Figure 6-15), and the maximum vehicle penetration is approximately 2.5 m at post 8 between segments 7 and 8 (Figure 6-16). Additionally, damage to the vehicle was minimal as shown in Figure 6-17. Therefore, the simulation results showed that the Jinzhou separator is not effective in stopping the vehicle from penetrating the non-motorized traffic path.

Figure 6-12: Impact Point for Jinzhou Separator

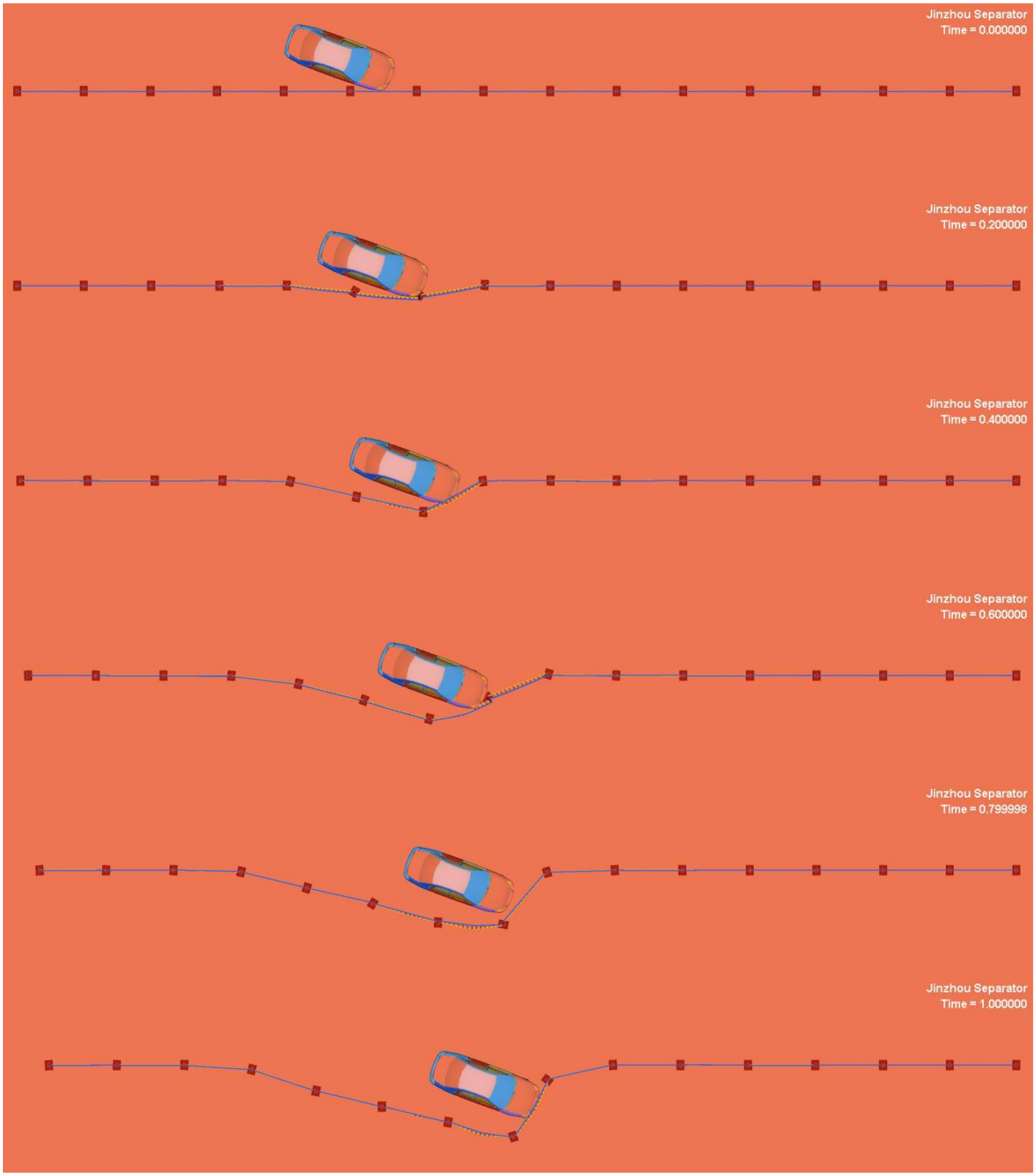


Figure 6-13: Sequential Images Showing a Top View of the Jinzhou Separator Simulation

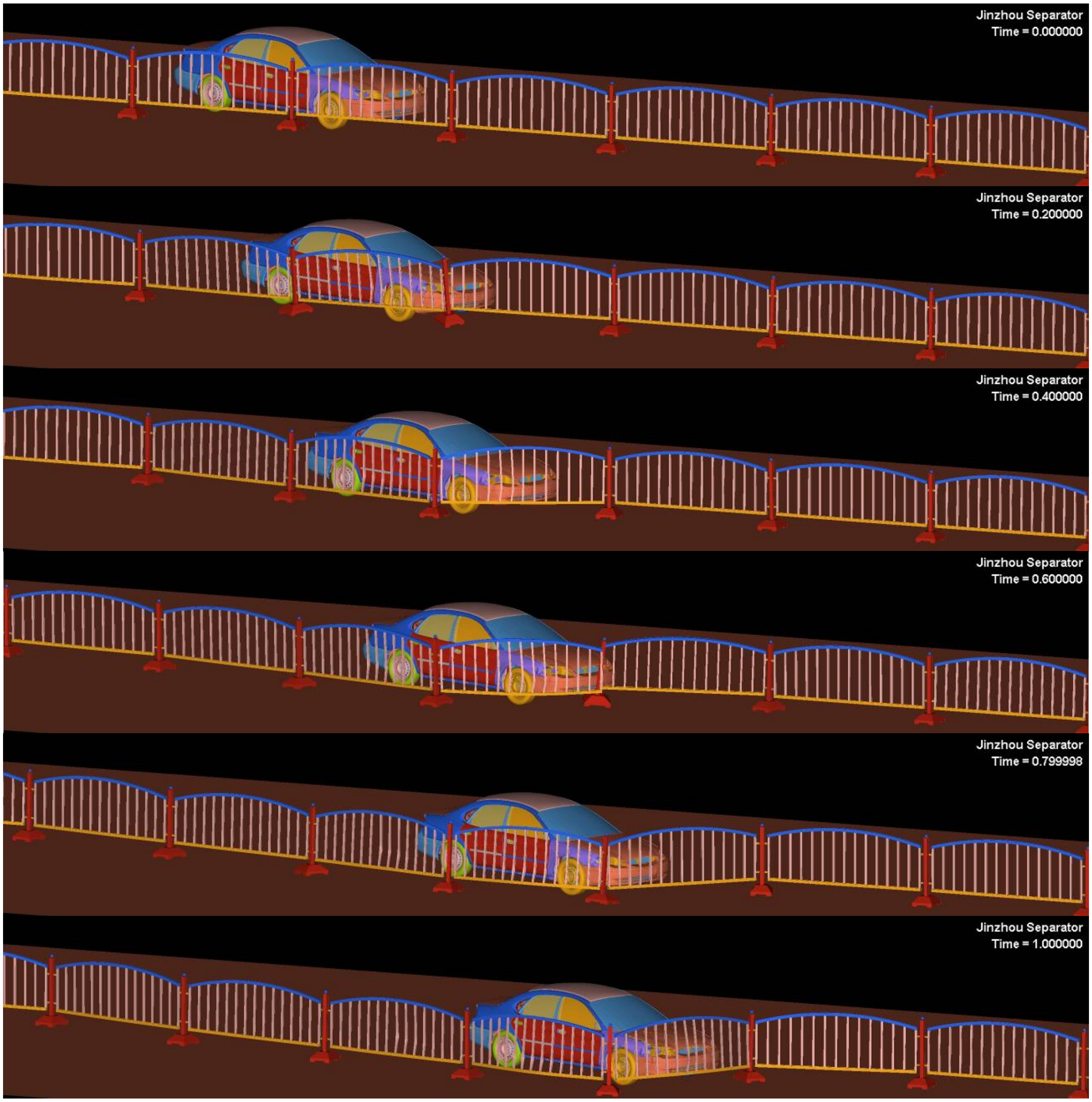


Figure 6-14: Sequential Images Showing an Isometric View of the Jinzhou Separator Simulation

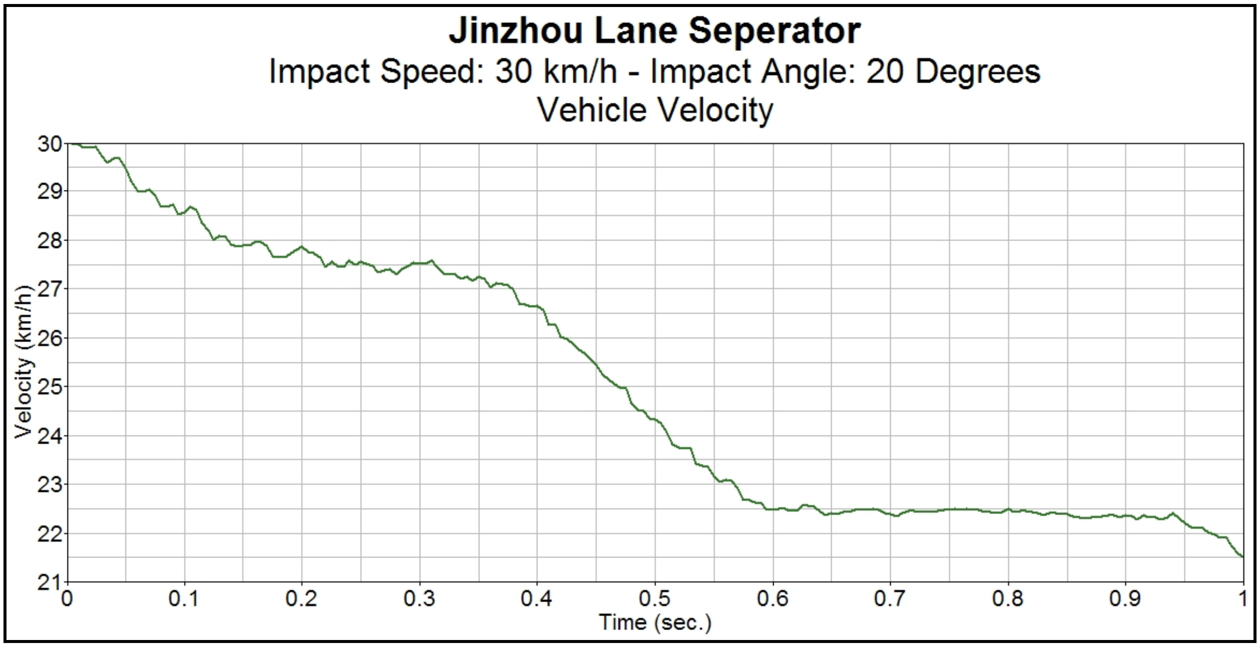


Figure 6-15: Vehicle Longitudinal Velocity for Jinzhou Separator

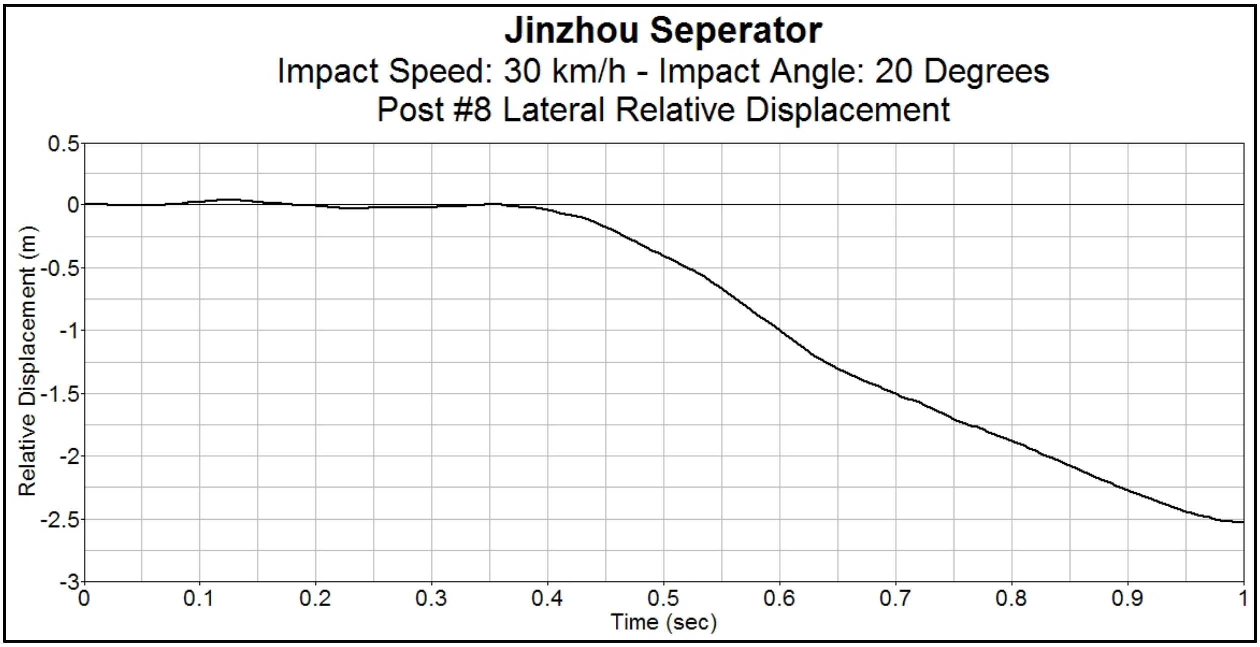


Figure 6-16: Post 8 Lateral Relative Displacement for Jinzhou Separator

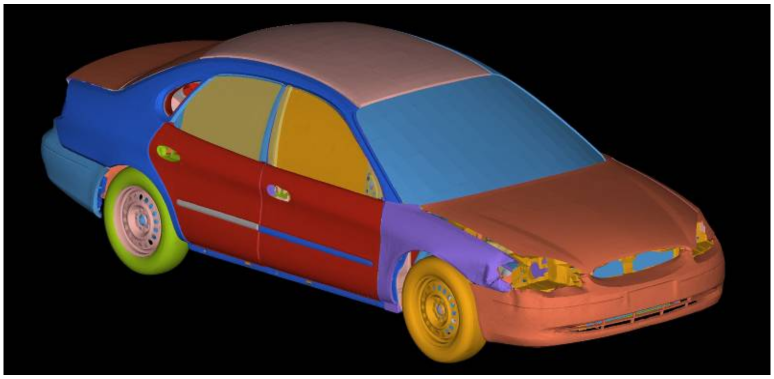


Figure 6-17: Post impact Vehicle Damage with Jinzhou Separator

6.5.2 Evaluation of Fushun Separator

Similar to the Jinzhou separator, the Ford Taurus travelling at a constant speed of 30 km/h impacts the Fushun separator at an angle of 20 degrees with the passenger side front bumper corner aligned to the center of segment 6 of the separator between posts 6 and 7 (Figure 6-18). Shortly after impact, the steel wire mesh of the separator yielded and bent slightly at the impact point following the vertical cross sectional shape of the bumper corner. The vehicle continues its forward trajectory, pushing segment 6 of the separator with 0.5 km/h reduction in longitudinal velocity. At 0.125 seconds, the front bumper contacts the 225 kg concrete base, causing damage to the passenger side fender and front bumper. From 0.125 seconds to 0.25 seconds the vehicle pushes the concrete base of post 7, laterally causing a 12.5 km/h reduction in vehicle velocity to 17 km/h. At 0.325 seconds, the concrete base of post 7 separates completely from the steel post. The vehicle then continues its forward trajectory at a constant 17 km/h impacting segment 7 of the separator. Sequences of images from the Jinzhou separator simulation are shown in Figure 6-19 and Figure 6-20.

After 0.6 seconds of total simulation time, the vehicle's velocity is reduced from 30 km/h to 17 km/h (Figure 6-21) and the maximum vehicle penetration is approximately 1.4 m at post 7 between segments 6 and 7 (Figure 6-22).Additionally, damage to the vehicle was limited to the passenger side bumper and front fender as shown in Figure 6-23. Although the simulation results of the Fushun separator showed that it performs better than the Jinzhou separator through reducing the vehicle's velocity by 12.5 km/h with 1.4 m of penetration, it is still not effective in stopping the vehicle from penetrating the non-motorized traffic path.

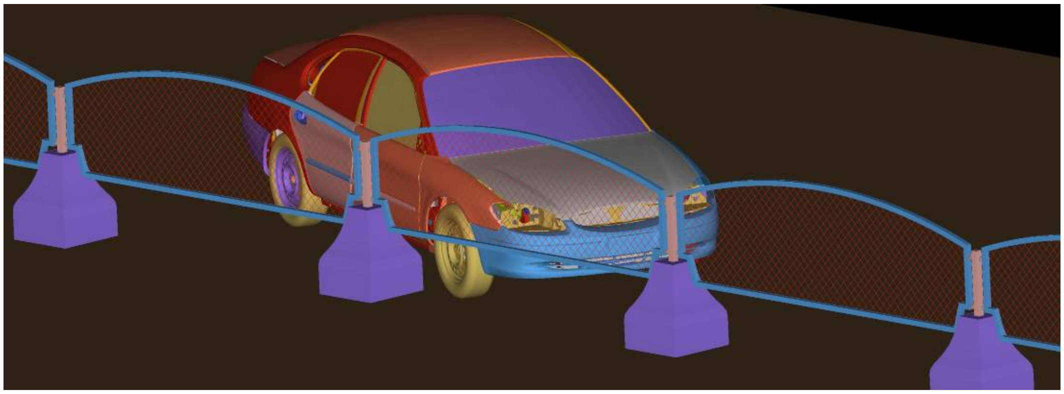


Figure 6-18: Impact Point for Fushun Separator

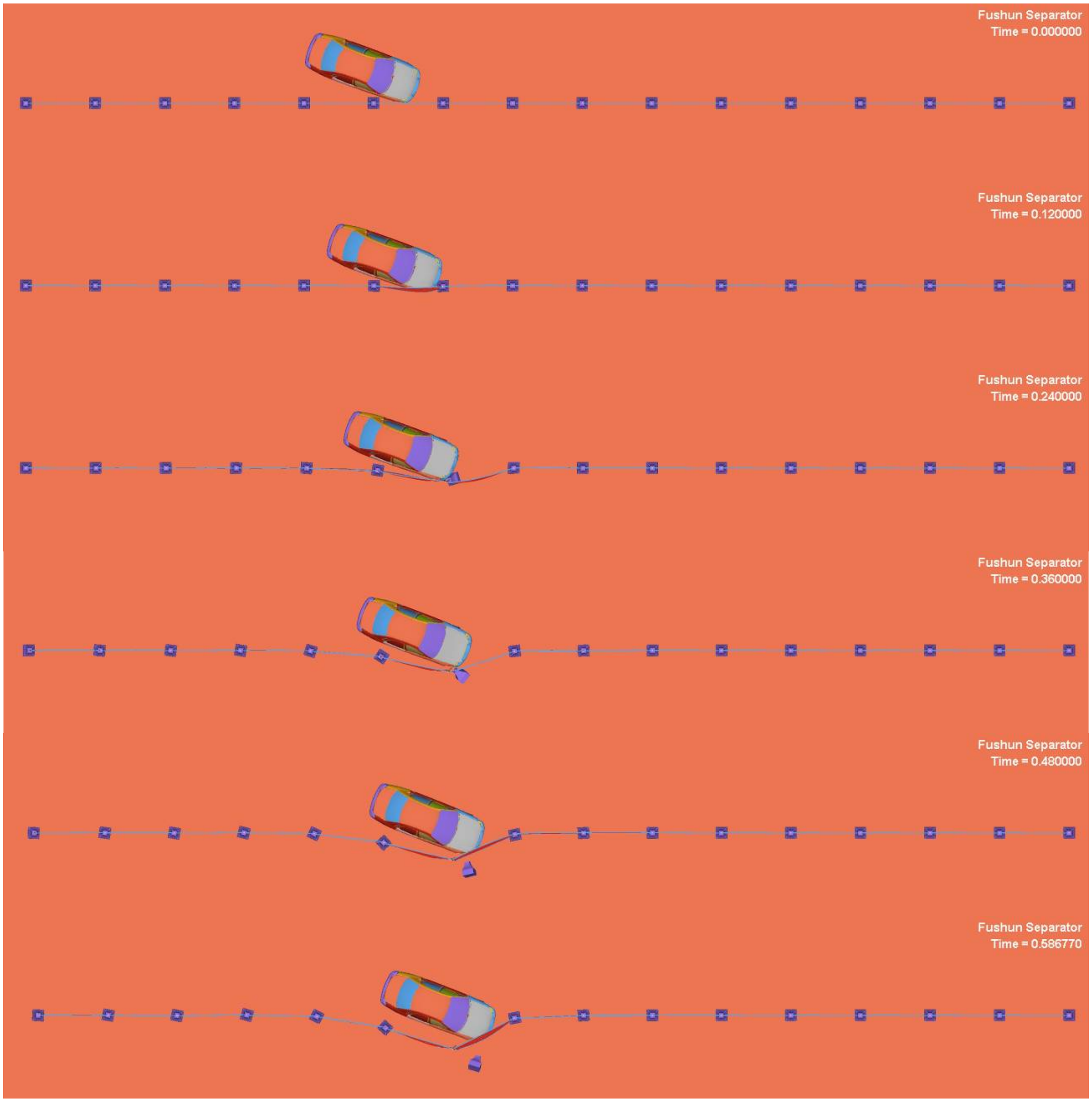


Figure 6-19: Sequential Images showing a top View of the Fushun Separator Simulation

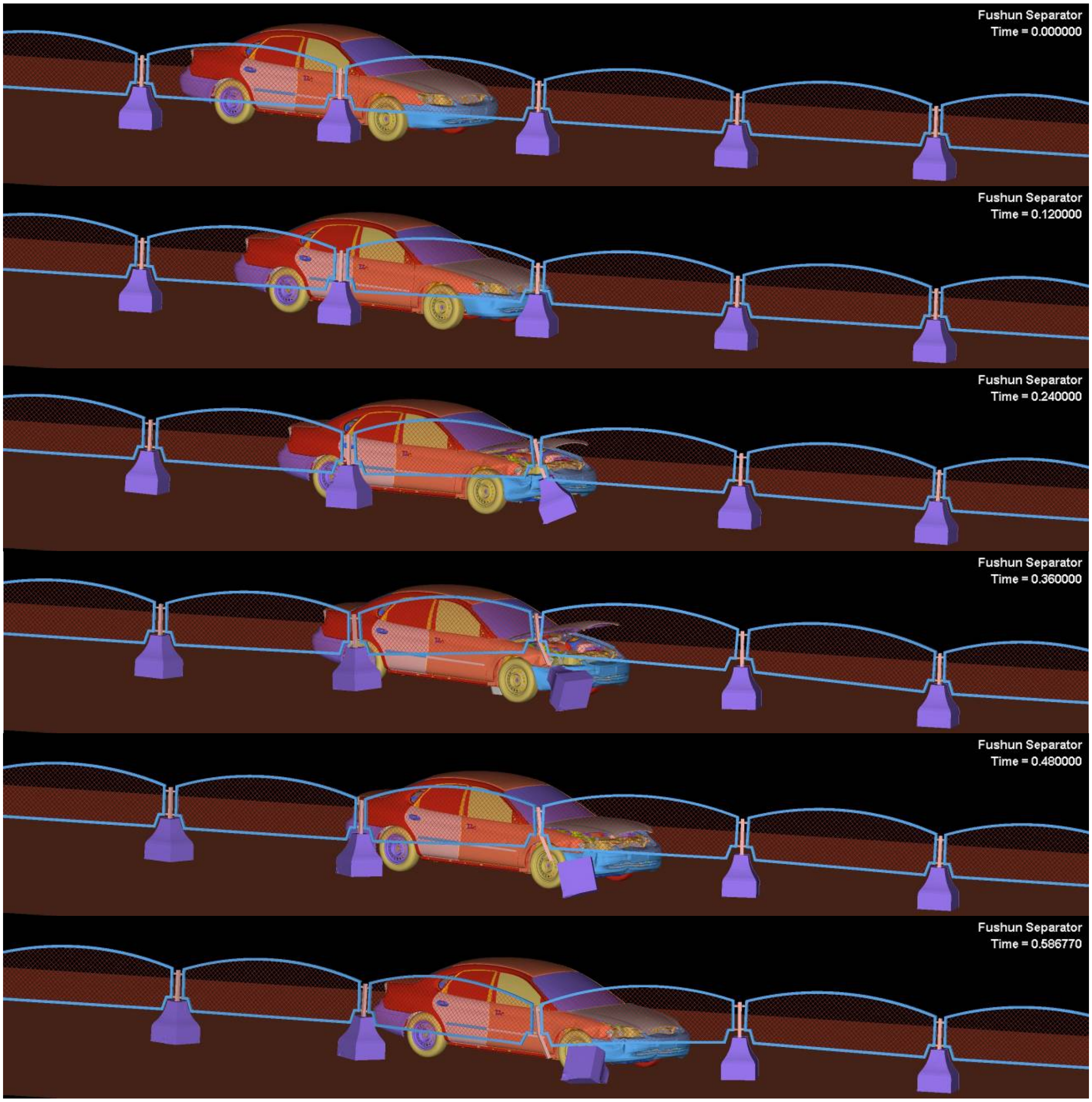


Figure 6-20: Sequential Images Showing an Isometric View of the Fushun Separator Simulation

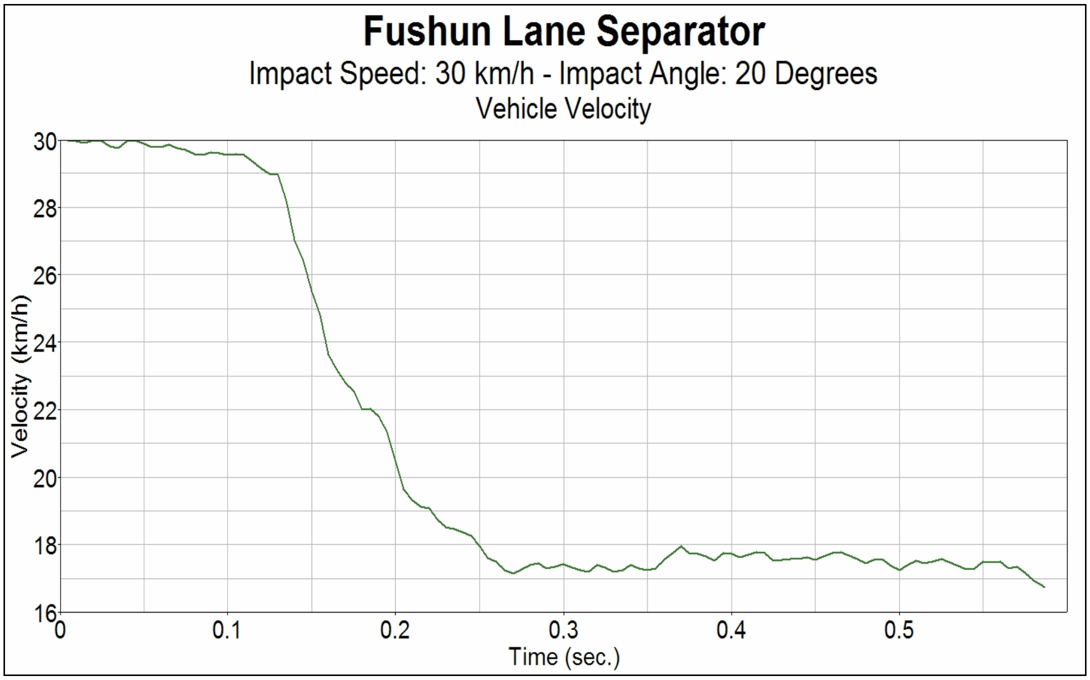


Figure 6-21: Vehicle Longitudinal Velocity for Fushun Separator

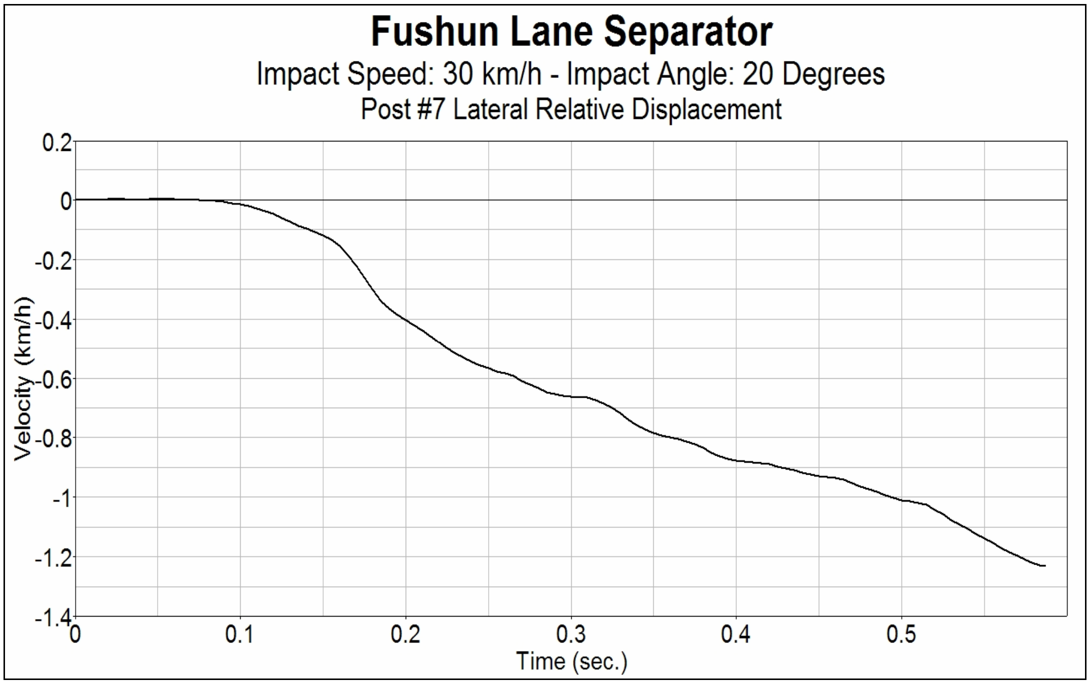


Figure 6-22: Post 7 Lateral Relative Displacement for Fushun Separator

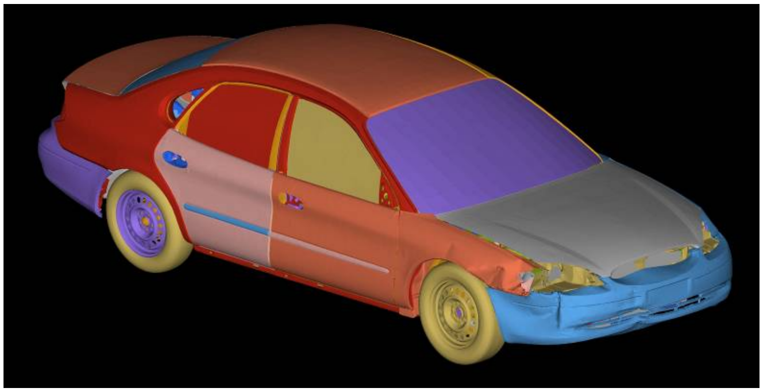


Figure 6-23: Post impact Vehicle Damage with Fushun Separator

6.6 Lane Separators Crashworthiness Findings

In this chapter, finite element simulations were conducted to determine the crashworthiness of two lane separators developed for the cities of Fushun and Jinzhou in China. The lane separators are designed to provide a physical separation between motorized and non-motorized traffic for a mobile and safe transport network for road users.

Finite element models of the lane separators were developed based on geometry extracted from drawings supplied by The World Bank. A fine mesh was used throughout both models to ensure accurate contact behavior and interaction between the vehicle and the separators. Additionally, appropriate material properties were implemented into the FE models. Each separator FE model was combined with the surrounding paving and a 2001 Ford Taurus FE model previously developed. The initial and boundary conditions (initial vehicle speed, impact angle, and barrier constraints) were incorporated in the model, and appropriate contact definitions were assigned to capture the interactions between the different components.

Simulations of both lane separators were performed to predict their crashworthiness. In addition to the 3-Dimensional animation, data from the simulations included vehicle velocity at the center of gravity in the longitudinal (x-axis) and relative displacement of the separators.

Results from the simulations showed that the Jinzhou separator had a maximum relative displacement of 2.5 m at a vehicle velocity of 21.5 km/h, and the Fushun separator had a maximum relative displacement of 1.2 m at a vehicle velocity of at 17 km/h (Figure 6-24).

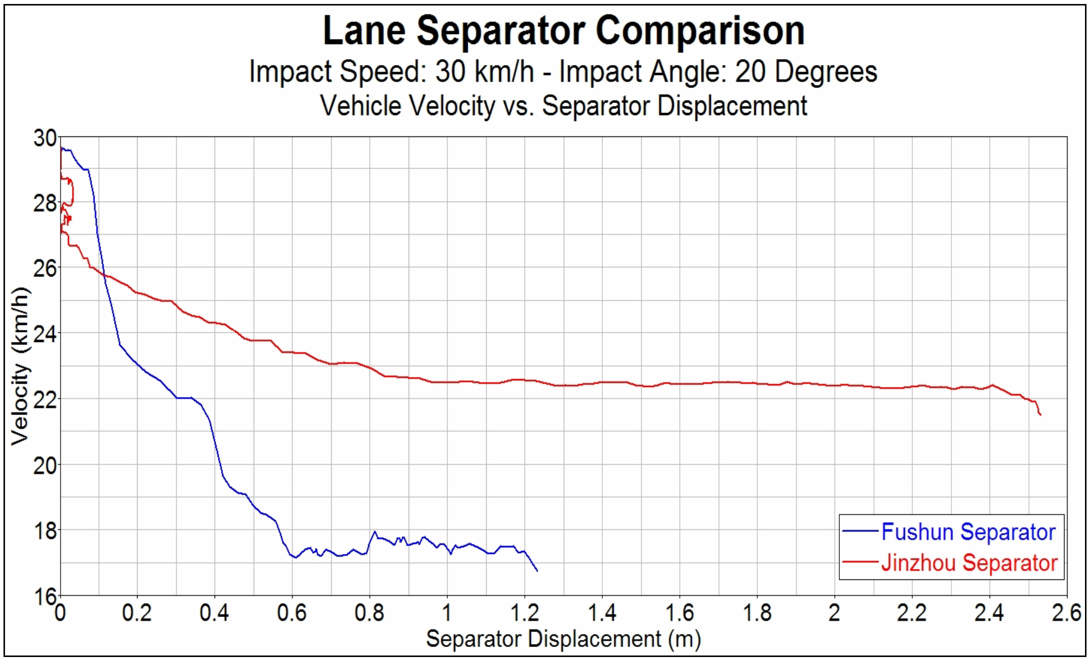


Figure 6-24: Vehicle Velocity and Separator Displacement Comparison

Therefore, and based on these results, both separators were not effective in preventing the vehicle from penetrating into the non-motorized traffic path. However, it should be noted that despite the fact that both separators could not prevent the car from penetrating the non-motorized traffic path, the performance of the Fushun separator was better then that of the Jinzhou separator. For instance, at one meter of separator displacement, the vehicle velocity was 22.5 km/h for the

Jinzhou separator and 17.4 km/h for the Fushun separator highlighting the Fushun separator's ability in providing a better vehicle velocity reduction.

Based on these simulations and the fact that the maximum recommended separator displacement is one meter (approximate position of cyclists), it is recommended that a fixed type of separator be used in order to provide adequate protection for the non-motorized traffic. Alternatively, both lane separators can be modified with fixed anchors to minimize penetration into the non-motorized traffic path.

CHAPTER 7

ECONOMIC APPRAISAL MODEL

7.1 Background

Cost-benefit analysis of transport schemes has a long history in developed countries, particularly as a means of allocation of scarce resources and as a method for ranking the economic viability of alternative schemes. Road investment programs typically produce benefits mainly composed of time savings and crash and casualty reduction. Monetary values of these benefits are required in order that costs and benefits can be compared in a common currency.

There has been much discussion in the economic literature concerning the valuation of human life, sometimes focusing on the unethical nature of any such calculation. However, for cost-benefit analysis what is in essence being valued is the benefit of an increase in safety or a reduction in risk. The value of statistical life is the level of investment that can be justified for the saving of one life. It is the valuation of a change in risk such that one life will be saved, rather than the valuation of the worth of a life of a specific individual.

One question to be addressed in determining values for use in a range of countries is whether it is appropriate to use different values depending on the level of income. Put more directly, should saving a life in a low-income country be afforded a lower value than in a high-income country? This is the wrong question. An underlying principle of economic theory is that the worth of something is determined by the price that people are prepared to pay for it. In essence, safety is a commodity like anything else in that achieving a reduction in risk requires expenditure i.e. a tradeoff between wealth and the desired level of safety. As will be seen in the following section on valuation methodologies, estimates of the value of statistical life are heavily influenced by income regardless of the method that is used. Both Willingness to Pay and the Human Capital/Lost Output approach provide estimates that are income dependent. A study of valuation in a range of European countries (COST 313 1993) found that about 40% of the variation between fatality values in the different countries could be accounted for by variation in Gross Domestic Product (GDP) per capita.

This chapter will:

- Discuss the background to valuation of safety benefits;
- Briefly review the main methodologies that are in use;
- Present recommendations for values for use in economic appraisal.

Valuation of the prevention of a fatality, often termed the value of statistical life, and valuation of serious injury are discussed separately.

7.2 Methodologies for Valuation of Value of Statistical life

It is not the intention of this paper to present a comprehensive review of methods for the empirical assessment of the value of a statistical life (VSL). Many such reviews exist in the economic literature (e.g. references 1-4). However, some brief description of the main methods is necessary in order to make recommendations on the way to obtain suitable values for the iRAP pilot countries that are generally applicable to a range of developing countries. Two main methods have been used to measure the value of the benefit of prevention of a road crash fatality: the Human Capital or Lost Output method and the Willingness-To-Pay method.

7.2.1 Human Capital or Gross Output Method

This approach consists of valuing death in accordance with the economic impact. The main component in this ex post approach is the discounted present value of the victim’s future output forgone due to death. To this are added market costs, such as the cost of medical treatment, and the cost of the crash itself, including administration cost, and property damage. This approach has clear disadvantages, as it focuses only on the economic effects of the loss of life and does not account for the value and enjoyment of life forgone. This grossly underestimates the true value of prevention of road crashes and will produce very significantly lower values than an ex ante estimate based on willingness to pay. As a partial correction for this shortcoming, a “pain, grief and suffering” component is sometimes added that is intended to represent “human cost”. Although this increases the value derived, it still results in a valuation that is generally much lower than values derived from the willingness-to-pay method, and the human cost component is usually arbitrarily determined.

7.2.2 Willingness-to-pay Method

The willingness-to-pay (WTP) approach consists of estimating the value that individuals attach to safety improvement by estimating the amount of money that individual would be prepared to pay to reduce the risk of loss of life. This ex ante approach involves some assessment of risk and the willingness of individuals to commit resources in exchange for reducing this risk to an acceptable level. This tradeoff between risk and economic resources, measured in terms of the marginal rate of substitution of wealth for risk of death or injury, accords well with the fundamental principle of social cost-benefit analysis that public sector allocative decisions should be based upon the preferences of those who will be affected by the decision concerned.

Estimates of WTP to prevent road crash risk are generally based on surveys designed to ascertain the amount of money that individuals say that they would be prepared to pay to reduce the risk of loss of life i.e. contingent valuation methods. Both revealed preference estimates, derived from actual purchases of risk reduction devices such as airbags, and stated preference estimates from hypothetical choices determined by questionnaires have been used. Although theoretically sound, there are practical problems with obtaining precise estimates of individual WTP for risk reduction. The willingness to pay to avoid a lost statistical life is influenced by context effect (the perceived seriousness of a road crash) and scale effects (the number of casualties the road crash will involve). Surveys have also shown that respondents are relatively insensitive to small variations in risk, and therefore in order to increase the precision of estimates survey methodologies have been devised to address these problems (Carthy, 1999).

However, despite the difficulties associated with accurate estimation of individual willingness-to-pay, it is generally accepted as the most valid method for assessment of the value of prevention of road risk. Economic evaluation of road traffic safety measures was discussed at Round Table 117 of the ECMT in October 2000. Both COST 313 and the ECMT Round Table concluded that willingness to pay is the preferred methodology as the human capital approach is not conceptually sound. The WTP method focuses on the right parameter and members of the Round Table agreed that "it was better to obtain an approximate measurement of the right parameter than to obtain an accurate measurement of the wrong parameter."

7.2.3 Rule of Thumb Approach

The WTP approach is conceptually appealing but has practical problems in being applied in developing countries as the methodological approach required to produce estimates is costly and requires sophisticated survey techniques. It is unlikely that there are existing results from willingness-to-pay studies to value statistical life in road crashes in each of the pilot countries. Ideally, it would be recommended that each country should carry out a willingness-to-pay survey to obtain an estimate of the value of statistical life in road crashes prior to any investment in road safety. However, given the costs and difficulties associated with such surveys, it is recommended that no new survey work would be appropriate for the iRAP Pilot countries. Carrying out WTP surveys in each country is not a viable option in terms of either cost or timeliness for completion of the pilot studies, quite apart from the intrinsic difficulty of producing reliable estimates.

An alternative approach has been investigated that explores the practicality of deriving a relatively simple "rule of thumb" drawing on available data and results from both willingness-to-pay and human capital studies from a range of countries. This started from the hypothesis that the level of income in a country is a primary determinate of the value of statistical life. This is obviously the case for values based on the human capital approach, but is also valid for WTP values as willingness to pay is influenced by ability to pay. Data were collected for a range of developed and developing countries and ratios of VSL to GDP per capita were calculated.

Table 7-1 shows a list of official values of statistical life used in some developed countries in economic appraisal of road safety schemes. The values for New Zealand, Sweden, UK and USA are based on the WTP method. The rest are mainly Human Capital based, but the estimate for the Netherlands includes a significant element for pain, grief and suffering.

Table 7-2 shows a list of values of statistical life for some developing countries. The majority of the values were based on the Human Capital approach and therefore the values are likely to be much lower than values derived from a WTP approach.

For developed countries, the ratio of the Value of Statistical Life to the per capita GDP varies between 42 and 86 with a mean and median of 63. If only the countries using WTP, plus the Netherlands and Iceland, are considered, both the mean and the median are 74.

Table 7-1: Official Values of Statistical Life for Developed Countries

Country	Official VSL	Per capita GDP	VSL/ per capita GDP	Year	Currency	Method
Australia	1,832,310	40,654	45	2003	Aus $	HC
Austria	2,676,374	31,028	86	2006	€	WTP
Canada	1,760,000	36,806	48	2002	C$	HC
France	1,156,925	27,232	42	2005	€	HC
Germany	1,161,885	26,753	43	2004	€	HC
Iceland	284,000,000	3,840,943	74	2006	ISK	HC+PGS
Netherlands	1,806,000	28,807	63	2002	€	HC + PGS
New Zealand	3,050,000	37,536	81	2005	NZ$	WTP
Sweden	18,383,000	295,436	62	2005	SK	WTP
United Kingdom	1,384,463	19,663	70	2004	£	WTP
United States	3,000,000	36,311	83	2002	$	WTP

For Developing countries and with the exception of Malaysia (WTP value), the ratio of Value of Statistical Life to per capita GDP ranges between 14 and 62 with a mean of 42 and a median of 40. Including Malaysia raises the mean slightly to 44. The higher Malaysian ratio is most likely to be due to the use of a WTP approach rather than a Human Capital (HC) approach, and although India's value based on WTP is not as high as that of Malaysia, it is higher than average. A TRL study on valuation in developing countries recommends adding 28% for pain, grief, and suffering to values obtained from human capital methods.

Table 7-2: Values of Statistical Life for Developing Countries

Country	VSL	Per Capita GDP	VSL/per capita GDP	Year	CU	Method
Cambodia	18,864	317	60	2002	$	HC
Philippines	41,330	982	42	2003	$	HC
Thailand	2,741,064	85,890	32	2002	B	HC
Vietnam	162,620,000	7,582,788	21	2003	D	HC
Lao	4,617	336	14	2003	$	HC
Indonesia	255,733,113	8,645,085	30	2002	Rp	HC
Malaysia	1,200,000	15,811	76	2003	RM	WTP
India	1,311,000	23,578	56	2004	Rs	WTP
Myanmar	4,806,909	144,967	33	2003	MK	HC
Bangladesh	889,528	16,169	55	2002	Tk	HC
Latvia	276,327	4,807	57	2006	LVL	HC
Poland	1,056,376	27,585	38	2006	PLM	HC
Lithuania	1,018,269	16,405	62	2003	LTL	HC

If we compare the ratios between developed countries (Table 7-1) and developing countries (Table 7-2), it is clear that the developed countries' ratios tend to be higher particularly when they are based on a WTP approach. However, what is striking from both these tables are the relatively clustered values of VSL/per capita GDP if countries are grouped according to the methodology used, and although the ratios for developing countries are more variable, overall the range of ratios is narrower than might have been expected prima facie. This finding gives some support to the concept of a rule-of-thumb approach based on the ratio of VSL to GDP per capita for obtaining workable estimates of the Value of Statistical Life for developing countries.

Regression Analysis:

The strength of the relationship between VSL and income levels was explored further using log linear regression to estimate an equation of the form:

$$\log_n (VSL) = a + b^* \log_n (GDP/Capita) + c^* \text{Method} \qquad (7.1)$$

where Method = 1 if willingness to pay methodology is used to derive VSL

0 if otherwise

Local currency data were converted to 2004 International \$ values for this analysis. The regression resulted in an equation with a Radj^2 value of 97%, and derived values of VSL/GDP per capita that averaged 53 across all countries in Tables 1 and 2.

Table 7-3: VSL in International 2004 $

Country	VSL 2004 International $	GDP/Capita 2004 International $	Method
Australia	1,304,135	28,935	HC
Austria	3,094,074	35,871	WTP
Bangladesh	71,066	1,710	HC
Canada	1,427,413	29,851	HC
France	1,252,083	29,472	HC
Germany	1,257,451	28,953	HC
Iceland	3,303,555	44,679	HC+PGS
India	147,403	2,651	WTP
Indonesia	92,433	3,125	HC
Latvia	1,042,743	18,140	HC
Lithuania	746,531	12,027	HC
Malaysia	722,022	9,513	WTP
Myanmar	51,245	1,545	HC
Netherlands	1,944,026	31,009	HC + PGS
New Zealand	2,033,333	25,024	WTP
Poland	573,806	14,984	HC
Singapore	924,240	25,034	HC
Sweden	2,015,680	32,394	WTP
Thailand	222,056	6,958	HC
UK	2,292,157	32,555	WTP
USA	3,000,000	36,311	WTP
Vietnam	53,063	2,475	HC

The regression equation is:

$$\log_n(\text{VSL}) = 2.519 + 1.125 * \log_n(\text{GDP/Capita}) + 0.496 * \text{Method} \qquad (7.2)$$

Although the analysis is based on only 22 countries, it supports the proposal to use the ratio of VSL to GDP per capita as a rule of thumb method to derive estimates of VSL in the pilot countries.

If we set the method to be a WTP approach, the regression equation will be reduced to:

$$\log_n (\text{VSL}) = 3.015 + 1.125 * \log_n (\text{GDP/Capita}) \qquad (7.3)$$

The shape of this equation is approximately linear, which supports again the use of a ratio of VSL to GDP per Capita while estimating Value of Statistical Life for the iRAP purposes. The proportionality assumption between VSL and GDP per capita is compensated for while doing the sensitivity analysis and changing the ratio.

Another regression equation was used to derive the ratio of VSL to GDP per capita to be used as the rule-of-thumb for the iRAP Economic Appraisal Model. The regression equation used the ratio of VSL to GDP per capita as the independent variable and the Method used to derive the value of statistical life as the dependant variable.

The regression equation is:

$$\text{VSL/per Capita GDP} = a+b* \text{Method} \qquad (7.4)$$

where Method = 1 if a WTP approach was used

0 if a Human capital approach was used

The regression resulted in an equation with Radj^2 value of 58%.

$$\text{VSL/per Capita GDP} = 41+30*\text{Method} \qquad (7.5)$$

If we set the method to be the WTP, the mean value of the ratio of VSL to GDP per capita will be 71 with a 95% confidence interval of [55,89].

7.2.4 Preferred Method

The advantage of a rule-of-thumb approach is that it will ensure consistency between the different countries and will avoid bias from surveys of unknown reliability. The disadvantage is that it has to rely on evidence from a limited number of countries for which acceptably reliable estimates of the value of statistical life are available. As discussed above, values based on willingness-to-pay are preferable to those based on human capital, but only a handful of countries currently use such values. However, the evidence from Table 1 shows that if the estimates use WTP or include an allowance for human costs, the ratio of VSL to GDP per capita is likely to lie in a fairly narrow range between about 60 and 80. This is supported by the regression analysis.

It is therefore recommended that a reasonable rule of thumb to use in the iRAP project for the default values for the economic appraisal model is 70 as a central ratio value, with a range of 60 to 80 for sensitivity analysis**.** This also accords with the WTP estimate of VSL/GDP per capita for Malaysia.

This approach will provide values for the benefits of fatality reduction that reflect the level of income in each country, but as the estimates will be based largely on data from developed countries; the values may also reflect the higher level of demand for safety in such countries. This is considered to be appropriate since one of the aims of iRAP is to raise demand for safety improvement within developing countries.

7.3 Methodology for Valuation of Value of Serious Injury

The main objective of the safety rating of infrastructure is to reduce the number of fatalities and serious injuries through mass action programs following the road inspection and its results. The economic appraisal model will take into consideration the benefit from reducing the number of both fatalities and serious injuries and therefore an estimation of the cost of a serious injury is necessary.

The Human Capital approach requires that an estimate of medical costs should be included. For fatalities, medical costs are relatively insignificant but for non-fatal casualties these are a significant component and rise with severity of injury. Treatment of serious trauma is a major cost to health services in all countries. Obtaining estimates of medical costs may be difficult in developing countries and the availability of data needs to be explored for each pilot country.

A possible method that could be used to estimate the value of serious injury in developing countries would be to consider the relationship between fatal and serious injury values in selected countries. This would need to be adjusted to reflect the distribution of injuries within the serious category in each of the pilot countries.

Comparison of values for serious injuries used in different countries is more difficult than comparison of fatality values. The definitions of what is included as a serious casualty vary considerably, even between developed countries. In some countries, an injury is defined as serious if the victim is hospitalized, whereas in other countries a wider definition is used. Injury data are often less reliable than fatality data and are more prone to under-reporting particularly of less severe injuries. This may bias the data in countries with poor data collection methods towards the more severe end of the injury spectrum. The distribution of severity in a country will also be affected by the modal split of travel, so that countries with higher proportions of pedestrians, cyclists, and motorcyclists will have injury distributions that are weighted towards more severe injuries.

As a starting point, the relationship between the value of statistical life and the value assigned to a serious injury was examined in each of the countries in Table 7.1 to see whether, despite the definitional problems, any consistency could be found that might inform an approach for estimating injury values in the pilot countries. The results are shown in Table 7-4.

Table 7-4: Serious Injury Data for Developed Countries

Country	Fatalities	Serious Injuries	VSL	VSI	Serious Injuries/ Fatalities	VSI/VSL %
Australia	1,634	22,000	1,832,310	397,000	13.4	22%
Austria	730	6,774	2,676,374	316,722	9.2	12%
Canada	2,936	17,830	1,760,000		6.1	
France	5,318	39,811	1,156,925	124,987	7.5	11%
Germany	5,842	80,801	1,161,885	87,267	13.8	8%
Netherlands	987	11,018	1,806,000		11.1	
New Zealand	405	3,950	3,050,000	535,000	9.8	18%
Sweden	440	4,022	18,383,000	3,280,000	9.1	18%
United Kingdom	3,221	31,130	1,384,463	155,563	9.7	11%
United States	42,815	356,000	3,000,000	464,663	8.3	15%

The numbers of fatalities and serious injuries are for the same year that the latest official value for statistical life was established and therefore the year may vary between the countries (See Table 7-1). The cost associated with the fatality and serious injury is expressed in local currency units. The value of serious injury relative to the value of statistical life as shown in the final column of the table above will be affected by the definition of serious injury used in each country. The wider the definition, the lower will be the ratio with all other things being equal. This assumption is supported by the relatively low ratio for the UK where the definition of serious injury is relatively broad compared with many other countries where only hospitalized casualties are included. Whereas for the fatality ratios in Table 1, the highest value was just under twice the lowest value, the highest value for the injury value as a percentage of the fatality value shown in Table 4 is nearer three times the lowest value. There is also an absence of clustering by estimation methodology with the UK closest to the value for France despite the different methodologies used. This variation makes the derivation of a simple rule of thumb problematic.

Ideally, an adjustment based on information about the distribution of injury type within the serious category would be required in order to correct for definitional bias and for the effect of modal split on the distribution of injury by severity. One possibility would be to obtain information on AIS distributions for a range of countries.

The Abbreviated Injury Scale (AIS) was conceived more than three decades ago as a system to describe the severity of injuries. Its original purpose was to fill a need for a standardized system for classifying the type and severity of injuries resulting from vehicular crashes. The AIS injury severity values are consensus-derived and range from 1 (minor) to 6 (fatal).

Table 7-5: Description of AIS Code

AIS Code	Description
1	Minor
2	Moderate
3	Serious
4	Severe
5	Critical
6	Maximal

The AIS does not assess the combined effects of multiple injuries. The most widely used system based on AIS is the Maximum AIS (MAIS), which categorizes casualties according to the most severe injury suffered. The MAIS is the highest (i.e., most severe) AIS code in a patient with multiple injuries. It is widely used to describe the overall injury to a particular body region or overall injury to the whole body. A person who is seriously injured in a car crash is most likely to sustain an MAIS 3, 4, or 5 injuries.

Ideally, in order to value serious injury, the average value of an MAIS 3-5 should be calculated based on the distribution of the MAIS 3, 4, and 5 within this "Serious Injury" category. This requires information on the distribution of injury by MAIS and also estimates of values of prevention for each MAIS category. Such data are difficult to find even in developed countries and unlikely to be available for developing countries.

Crash Injury databases from various developed countries were examined. Data for both injury distribution and value of prevention are available by MAIS for the U.S. from the National Automotive Sampling System NASS database. The U.S. data also provide information for pedestrian injury by MAIS from the Pedestrian Crash Data System (PCDS). The only crash data in developing countries that was classified on an MAIS scale is the data from the Injury Surveillance Program in Thailand.

The methodology suggested to value the cost of a serious injury is to apply the MAIS 3-5 distribution of the injuries to the U.S. cost of MAIS and derive a relationship between the value of MAIS 6 (Fatality) and the average value of MAIS3-5 (serious injury).

Since the majority of crash injured persons in developing countries are from the vulnerable road users category (pedestrians, cyclists, motorcyclists), it is important to apply this methodology to a set of pedestrian crash injury data as well as a set of crash data from a developing country. Therefore, the 2 injury databases used to estimate the mean ratio of value of serious injury to the value of statistical life are the U.S. Pedestrian Crash Data System (PCDS) and the injury data from the Injury Surveillance Program in Thailand.

The distribution of injury data for all road user casualties from the NASS-CDS database for the years 2000-2005 is shown in Table 7-6. Table 7-7 shows US injury cost values by MAIS.

Table 7.6: Total MAIS 3-5 Injury Severity Distributions 2000-2005

MAIS	Number	%
3	397,241	67.1
4	124,019	20.9
5	71,009	12.0
Total	592,269	**100.0**

Table 7-7: Cost of MAIS 3-6 in the US

MAIS	Cost ($)
3	175,000
4	565,000
5	2,290,000
6	3,000,000

From Tables 7-6 and 7-7 a weighted average value for MAIS 3-5 can be derived. This value is $510,000 which is 17% of the U.S. VOSL.

Tables 7-8 and 7-9 show the distribution severity of pedestrian injuries in the U.S. (PCDS 1994-1998) and in Thailand (Injury Surveillance Program 2004-2006) respectively. Note that the PCDS database consists only of 512 pedestrian cases of which 147 cases are serious injuries (MAIS3+) but this sample is the biggest in depth pedestrian injury study worldwide.

It is surprising that the distribution of injuries in Thailand (Table 7.10) is so close to the U.S. distribution for all road users (Table 7.6) since it would be expected that the proportion of vulnerable road users injured in Thailand would be higher than in the U.S. where motor vehicles predominate.

Table 7-8: MAIS 3-5 Pedestrian Injury Severity Distribution in the US (PCDS Database)

MAIS	Number	%
3	74	50.3
4	34	23.1
5	39	26.5
Total	**147**	**100.0**

Table 7-9: MAIS 3-5 Pedestrian Injury Severity Distribution in Hong Kong

MAIS	Number	%
3	95	46.8
4	46	22.7
5	62	30.5
Total	203	**100.0**

Table 7-10: MAIS 3-5 Injury Severity Distribution in Thailand

MAIS	Number	%
3	49,921	67.9
4	14,572	19.8
5	9,010	12.3
Total	73,503	100.0

From Table 7-8 the average cost for a pedestrian MAIS 3-5 injury in the U.S. is $826,000, which is 28% of the U.S. VOSL. If the injury distribution in Thailand in Table 7.9 is used with the U.S. costs in Table 7.7, the weighted average cost for a serious injury is $511,000 or 17% of the U.S. VOSL.

To summarize these results:

1- The value of a serious injury in the U.S. is 17% of the value of life
2- The value of a pedestrian serious injury in the U.S. is 28% of the value of life
3- The value of a serious injury in Thailand is 17% of the value of life (using U.S. cost table , Table 7-7)
4- The value of a pedestrian serious injury in Hong Kong is 30% of the value of life (using US cost table , Table 7-7)

It is important to note the scaling problems associated with the injury surveillance program in Thailand. This system is still using the AIS-85 coding system and needs to be updated to the AIS-2005 system. Also, it was observed that there was a difference in reporting between hospitals within the system, which includes 30 hospitals. If we apply the same methodology to the data from a particular hospital in Thailand (Khon Kaen regional hospital) where 48% of the seriously injured (MAIS3-5) sustained an MAIS 5 injury, the average value of serious injury will be about 40% the value of life and this may be due to an AIS coding problem.

Another observation to make is that the relative cost of an MAIS 3-5 to the cost of MAIS 6 in the U.S. is different than the one in developing country. For example, in the U.S., an MAIS 5 injury costs about 76% the cost of a fatality. This may not be the same in a developing country as some research has shown that the cost of an incapacitating injury is higher than the cost of a fatality when the last is derived using a Human Capital approach.

Taking all of the above into consideration, and with the absence of a reliable injury crash data system and the valuation of different injuries, it is recommended that a reasonable value of serious injury for the economic appraisal model is 25% of the value of life, with a range of 20% to 30% for sensitivity analysis. The equivalent values in terms of multiplier of GDP per capita are a central value of 17 with a range of 12 to 24 for sensitivity analysis.

7.4 Estimating the Number of Serious Injuries

The Casualty Estimation model will only generate the number of fatalities per km per year. Therefore there is a need to estimate the number of serious injuries per km per year. The model will use a default ratio of number of serious injuries to number of fatalities for a given length of the network. This ratio depends on the definition of serious injury to be adopted. The wider the definition is, the higher the ratio will be and the lower the value of serious injury will be.

In the methodology to estimate the value of serious injury explained above, it was agreed that an MAIS3+ injured person will be classified as "seriously injured”. This definition is widely used among researchers who use the AIS scale to classify the severity of injury.

Table 7-4, shows the ratio of serious injuries to fatalities in some developed countries, the definition of serious injury defers between countries. In general, a seriously injured person from a police crash data refers to a person being hospitalized. Per example, a person who is slightly injured but was admitted to a hospital for few hours will be considered seriously injured from a police report and therefore the definition is wide. That definition is used in the majority of the countries of Table 4. The ratio between serious injuries and fatalities in that Table ranges between 6 and 13.

For the same serious injury definition (being hospitalized), this ratio increases to 16 in some developing countries as reported in the ADB-ASEAN project shown in Table 7-11. The high operating speed, low seat belt/ helmet wearing rates, unforgiving roads in those countries may explain these higher ratios.

The definition of serious injury adopted in the iRAP tools, is narrower than just being hospitalized because an MAIS 2 injury can be hospitalized for few minutes or hours then being released, but an MAI3+ injured person will most likely stay over night in the hospital.

An equivalent to and average MAI3+ injured person will most probably be a person who is hospitalized for more than 24 hours on average and therefore with the lack of reliable in-country crash injury data it is recommended to use 10 as the default ratio of the number of serious injuries to the number fatalities and for sensitivity analysis this ratio will vary between 8 and 12.

Table 7-11: Ratio of Serious Injuries to Fatalities from ADB-ASEAN Project

Country	SI/F
Indonesia	14.7
Philippines	16
Thailand	14.5

7.5 Summary of the Economic Appraisal Model

Table 7-12 shows the values of life and serious injuries as percentages of GDP per capita that are recommended for use as default values as well as for sensitivity analysis for the Economic Appraisal of the countermeasures that will be generated. It also shows the value of serious injury and the ratio of number of serious injuries to number of fatalities to be used.

Table 7-12: Economic Appraisal Model Values

	lower	central	upper
Value of Life	**60*GDP/Capita**	**70*GDP/Capita**	**80*GDP/Capita**
Value of Serious Injury	**12*GDP/Capita (20% VSL)**	**17*GDP/Capita (25%VSL)**	**24*GDP/Capita (30%VSL)**
Number of Serious Injuries to number of Fatalities	**8**	**10**	**12**

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

Each year 1.2 million people die and as many as 50 million are injured or permanently disabled in road crashes. The burden of road crashes is the equivalent to that of Tuberculosis and Malaria, and costs between 2 and 5% of the world Gross Domestic Product.

In low and middle income countries, road crashes represent an especially serious health concern. More than 85% of the global death toll and serious crash injuries occur in developing countries. Whereas road deaths are expected to fall in high-income countries, they are likely to increase by more than 80% in the rest of the world.

In developing countries, it is the poor who are most vulnerable. Pedestrians, cyclists, motorcyclists and those using informal public transport (such as pickup trucks laden with people and goods) are many times more likely to be harmed on the roads.

A road protection score that can be used as an intermediate outcome measure for infrastructure safety was developed. The data analysis showed that the variation in road protection score can explain around 50% of the variation in the fatality rate for pedestrians. This percentage varies between countries, yet there will be a good correlation between road protection score and fatality rate, which leads to the conclusion of the correlation between the quality of the roads and safety.

Upgrading the existing network in low and middle income countries will lead to quickest results in reducing traffic fatalities and serious injuries, as compared to enforcement and education programs that may take up to a decade to be in place and effective.

The analysis carried out in this dissertation led to many conclusions with regards to the interaction between pedestrians, vehicles, and the road environment that comprise the system approach model in road safety.

The relationship between pedestrian risk of injuries and impact speed is not continuous. This assumption is statistically valid for the PCDS database but needs to be validated against other pedestrian databases with more accurate impact speed estimation.

Two plateaus are observed in the analysis of serious injury risk in the non-parametric (non-continuous) model. A relative constant risk of serious injury is observed for the speeds between 16 and 30 km /h (20%) and between 30-48 km/h (60%). Similar observations were concluded through MADYMO simulations. The pedestrian serious injury risk increases exponentially between 30 and 50 km/h (20 and 60 % respectively). This conclusion was made from the PCDS data analysis as well as the simulations.

Secondary impacts of the pedestrian with either the ground or the vehicle are severe but a pedestrian will always sustain serious injuries from the first impact with the vehicle's windshield for the speeds higher than 30 km/h. Therefore, it was concluded that there is a need to offer more head protection from the windshield impact. An outside air curtain parallel to the windshield for head protection was simulated and proven to be effective in reducing head injuries especially for the speeds lower than 60 km/h.

The Swedish Vision Zero concept of integration and separation is validated in this study. This concept suggests that if you can not lower the speed limit to 30 km/h where pedestrians are present, you should separate them from the vehicular traffic. Roads with speed limit higher than 30 km/h will not have a low road protection score (high rating) unless a sort of physical separation between pedestrians and vehicles is present.

To summarize, a speed limit of 30 km/h is suggested for urban areas with no separation, and a speed limit of 50 km/h in semi-urban areas with separation.

The crashworthiness of two designs of separation fences between road cyclists' path and vehicle lanes was evaluated through finite elements simulations. The simulations were carried out for 30 km/h. The goal of these separators is to prevent the vehicle from impacting the cyclist if a crash happens. It was concluded that these fences are not very effective unless they are anchored to the ground.

Value of life and serious injuries to be used in appraisal of road safety measures were derived in this study. The rule of thumb of 70 times the gross domestic product per capita is the estimate to be used in any country to value life in road safety. The conventional rule of 10%, that is the value of a serious injury being 10% the value of life, is not valid for developing countries. According to several crash injury databases analyzed in this study, it was concluded that the distribution of serious injuries in developing countries is different that the one in developed countries. The most severe injuries tend to be a dominant sub-category of the serious injury category. This is explained by the presence of vulnerable road users with no separation and high operating speeds in developing countries. As a result, an average value of a serious injury being 25% the value of life is suggested and highly recommended. These economic values will have a positive impact on justifying road safety measure by increasing their rate of return and cost-benefit ratios.

8.2 Limitations

It is important to highlight that this research have been carried out with a number of limitations especially in the data needed in some analysis. The major limitations faced were as follow:

- Lack of reliable pedestrian fatality and pedestrian flow data from developing countries associated with roads of known infrastructure characteristics in order to develop country specific fatality factors.
- Number of detailed pedestrian injury databases using the AIS scale in developing countries.
- Uncertainty or absence of Accident Modifications Factors (AMFs) for pedestrian crashes.
- Absence of injury criterion for pedestrian injuries, therefore conventional injury criterion for drivers and passengers are used (e.g. HIC, Chest Acceleration).
- Number of economic studies on the Value of Statistical Life in road safety in developing countries.

8.3 Recommendations

Several recommendations are suggested that may improve our knowledge of pedestrian safety and thus improve the countermeasures to be used.

- It is important to derive likelihood factors for different road attributes (e.g. crossing type) for roads in low and middle-income countries. Detailed and accurate pedestrian injury databases need to be developed and maintained in low and middle income countries. These databases should be used to derive injury risk functions for pedestrians.
- Further studies on the pedestrian injury biomechanics should focus on adult and child head brain, on child thorax and adult lower extremities. Finite element models for pedestrian simulations should be validated and used instead of multi-body models.
- Willingness-to-pay surveys should be carried out in several low and middle-income countries to estimate how much people are willing to invest to reduce their fatality risk from road crashes. These studies can lead to better estimate of value of life in road safety??? (DOES not make sense).
- It is recommended to include road safety as one aspect in the appraisal of road transport projects. Tools for the economic evaluation of road safety measures exist and this research emphasizes the evaluation of vulnerable road users' related measures.

Finally, it is important to compare the benefit of improving road safety with other benefits like reducing travel time, vehicle operation cost and carbon emission or other aspects that can be part of the evaluation of road projects.

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APPENDIX A

SYSTEMS APPROACH IN ROAD SAFETY POLICIES

A.1 Vision Zero – an operational framework for safe infrastructure

Perhaps the best example of a ‘systems approach’ is the Vision Zero philosophy adopted by the Swedish Government. Vision Zero provides a viable policy framework for sustainable safety whose basic principles can be applied in any country at any stage of development. The Vision states that “it can never be ethically acceptable that people are killed or seriously injured when moving within the road transport system”.

"…the speed limits within the road transport system should be determined by the technical standard of vehicles and roads so as not to exceed the level of violence that the human body can tolerate. Safer the roads and vehicles are; Higher the speed can be accepted”.

In all current road transport systems, the road user is expected to assume most responsibility for safety. In most countries, there are general rules that the road user should behave in such a way that accidents are avoided. If an accident occurs, at least one road user has, by definition, broken the general rule and the legal system can therefore act.

In contrast, Vision Zero explicitly states that the **r**esponsibility is shared by the system designers and the road use**r** according to the following principles:

1. The designers of the system are always ultimately responsible for the design, operation, and use of the road transport system, and are thereby responsible for the level of safety within the entire system.

2. Road users are responsible for following the rules for using the road transport system set by the system designers.

3. If road users fail to obey these rules due to lack of knowledge, acceptance, or ability, or if injuries occur, the system designers are required to take necessary further steps to counteract people being killed or seriously injured.

Investment in Sweden has been mainly directed at managing speed where there is a potential for conflict with other vehicles and providing better links between vehicle crash protection and the infrastructure. Other investments are directed towards more protective roadsides and a greater separation of road users where speeds exceed 70-90 km/h. For pedestrian safety, the aim is to restrict vehicle speeds to 30 km/h where there are potential dangers between vehicles and pedestrians, or else physically to separate cars and pedestrians. Much effort has been focused on collaboration with different system designers and stakeholders. They need to be part of the solution for a safe transport system.

A.2 The Dutch “Sustainable Safety” approach

The “Systems Approach” has also influenced the Dutch ‘Sustainable Safety’ policy conceived by the Institute for Road Safety Research and the Dutch Ministry of Transport, and developed in cooperation with local authorities. This 3-year program on “Sustainable Safety” was launched in 1998 then updated in 2006.

The Sustainable Safety vision builds upon the hierarchy of roads as proposed in the Buchanan report, and further elaborated by Janssen (1974), by making a distinction between "residential function" and "traffic function". Within the traffic function, two sub-functions are distinguished: "traffic flow management" (flow) and "making destinations along roads and street accessible" (provide access). The flow and access functions are strictly divided in the Sustainable Safety vision. For each function there is a separate road category (the area access function and the residential or area function are combined). The roads that connect both categories are distributors. A distributor may not only provide a flow function: it also is the link between both other categories. This combination will have to be manifest in a safe way in the design of a distributor (and an appropriate speed limit).

Given the fact that people make mistakes, do not always comply with rules and moreover that they are vulnerable, it is essential that latent errors in the traffic system are prevented in order to avoid a breeding ground for accidents. According to the Sustainable Safety vision, in order to prevent serious errors, environment and the task requirements must be reasonable for the majority of road users.. This will evoke desirable behavior as the road user knows what to expect and possible mistakes can be absorbed by a forgiving environment. This also makes the breeding ground for intentional or unintentional violations less fertile. Insofar violation behavior prior to traffic participation can be detected (such as alcohol consumption or not having a driving license), denying traffic access fits within sustainable safe road traffic.

Road users must be well informed and practiced to take part in traffic. If their skills and capabilities do not meet the environment and task requirements, they must be brought to safe behavior by means of specific measures. It is essential that road users are aware of their situation-dependent state, and consequently their task capability, to take adequate decisions that may prevent a possible accident. Because there are differences between road user capabilities, more experienced road users should be required to engage consciously in safe traffic behavior directed at less experienced road users. A forgiving driving style can absorb the emergence of accidents caused by other road users as a social system.

The vulnerable human has to be protected in traffic by the environment by means of structures that absorb the released kinetic energy in a crash. To this end, masses of vehicles sharing the same space need to be compatible. If this is not possible, then speeds need to be lowered. This system is embedded in a traffic engineering taxonomy of fast traffic flows on the one hand, and destination and residence on the other. Between these two extremes, traffic has to be guided in good, sustainable safe ways.

With this slightly adapted vision on sustainable safe road traffic, we finally arrive at the *five central principles*: functionality, homogeneity, recognizability, forgiveness, and state awareness. A short description of these principles is given in Table A-1.

Table A-1: The Three Original and Two New Sustainable Safety Principles: Forgiveness and State Awareness (Wegman, 2006).

Sustainable Safety principle	**Description**
Functionality of roads.	Mono-functionality of roads, arteries, area access roads, residential access roads, in a hierarchically structured road network.
Homogeneity of masses and/or speed and direction.	Equity in speed, direction and masses at medium and high speeds.
Forgiveness of the environment and of road users.	Injury limitation through a forgiving road environment and anticipation of road user behavior.
Predictability of road delineation and road user behavior by a predictable road design	Road environment and road user behavior that support road user expectations through consistency and continuity in road design.
State awareness by road user.	Ability to assess one's task capability.

APPENDIX B

INFRASTRUCTURE SAFETY MANAGEMENT SYSTEMS

Figure B-1 from the European Project RIPCORD shows the three proactive and two reactive approaches for the Road Infrastructure Management. In Figure B-2, the infrastructure safety management system is broken down by type of roads (new and existing roads).

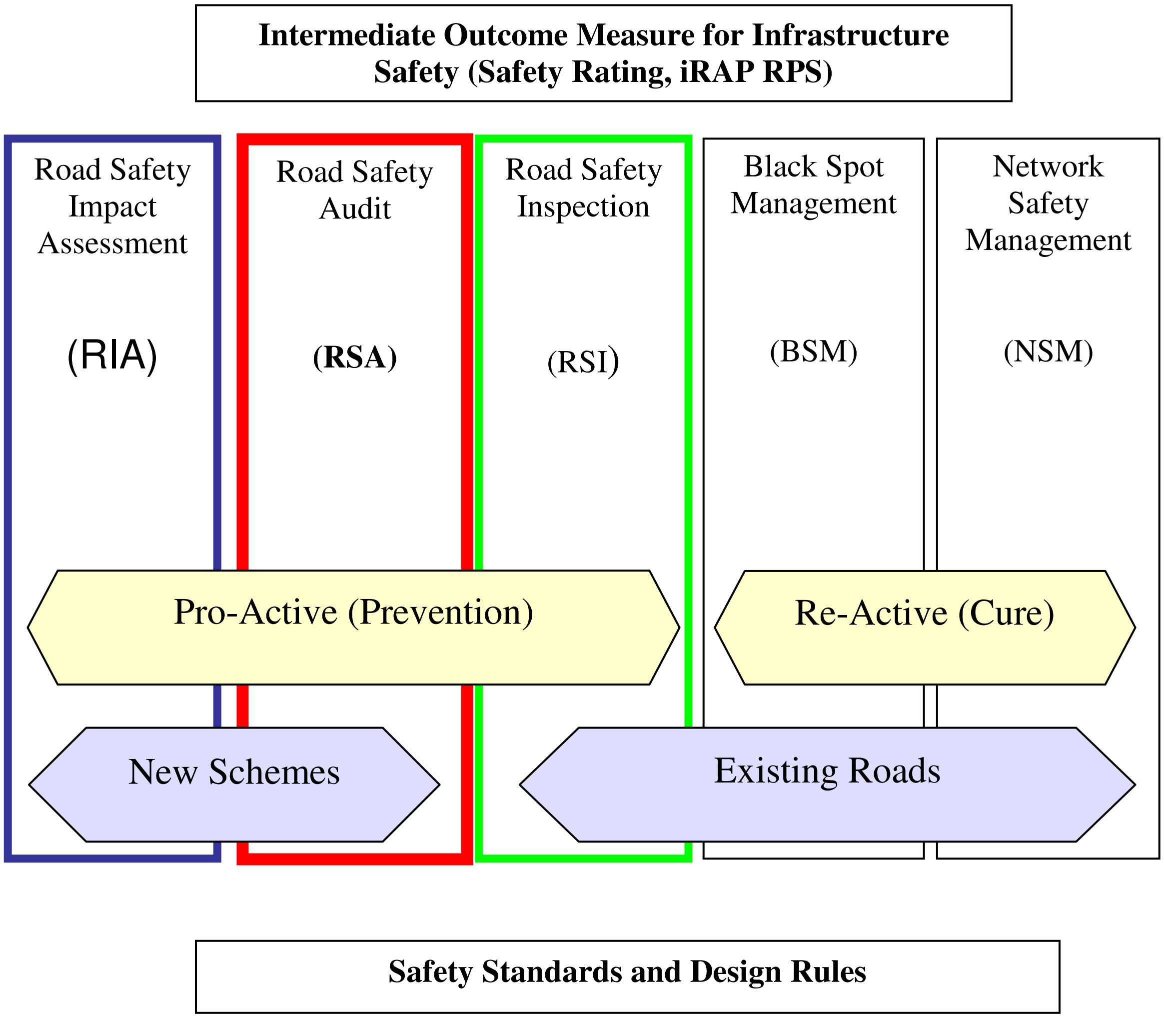

Figure B-1: Road Infrastructure Safety Management I, European Project RIPCORD-ISEREST (with Amendment)

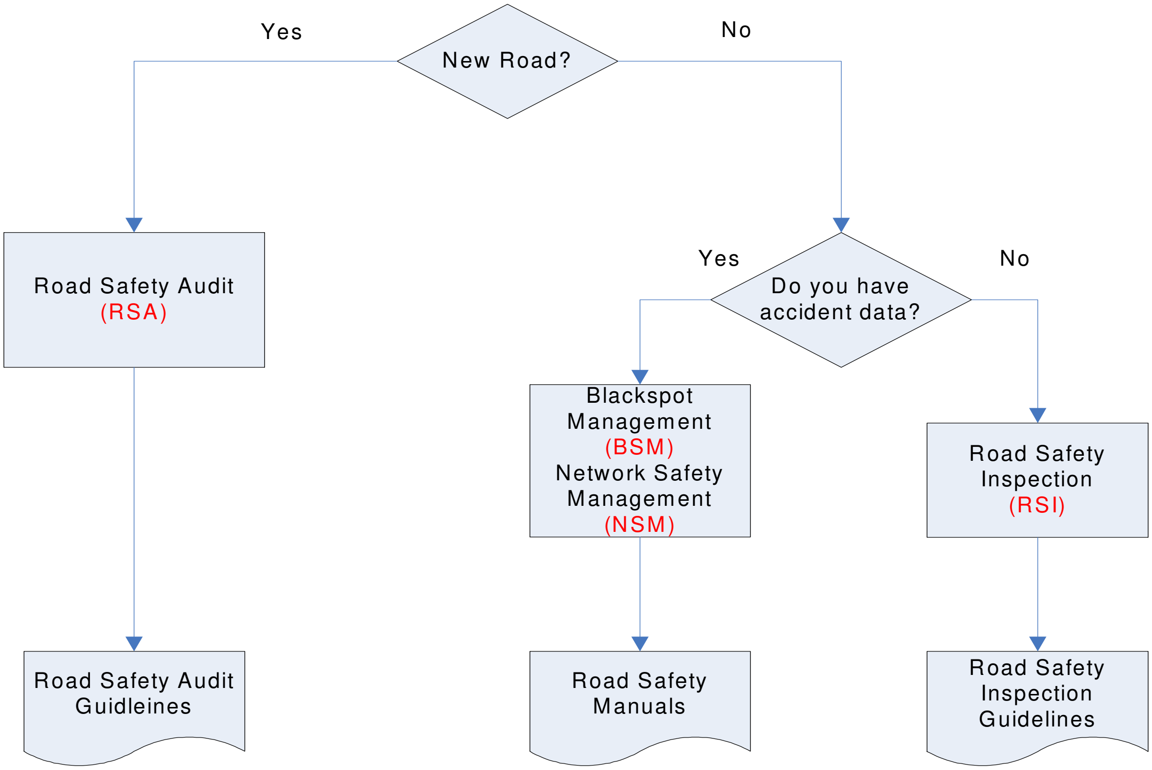

Figure B-2: Road Infrastructure Safety Management II

B.1 The Pro-Active Approaches

B.1.1 Road Safety Impact Assessment (RIA)

When decisions on large road projects or new road schemes are made, their impact on road safety is an important issue. A Road Safety Impact Assessment (RIA) can help identify the likely safety effects of different proposed roads or traffic schemes or policy actions (e.g. changing speed limit). It usually covers the whole road network, which is affected by the measure. Road impact assessment can be used for assessing the impact of plans with a wider scope on regional or national networks like a road safety plan or transport master plan.

B.1.2 Road Safety Audit (RSA)

Whenever road authorities plan new roads or whenever an existing road has to be redesigned due to changes in local conditions, the road designers have to consider a number of different aspects and interests in their schemes which have an effect on the design itself.

For several reasons, the project costs, the environmental restrictions, and political restraints, force the designer to make compromises which do not always lead to a design with the highest level of safety. Road safety aspects are mostly implicitly considered in the design standards and existing approval procedures usually check for compliance with design standards only. To avoid unsafe new roads, road safety audits have been developed in the UK and adopted by many other countries. During these audits, a team of road safety experts checks the schemes for any possible improvement with regards to road safety and inform the authorities about it. The main advantage of road safety audits therefore is that authorities can appropriate remedial measures before crashes happen.

B.1.3 Road Safety Inspection (RSI)

A road safety inspection is a systematic assessment of the safety standard of an existing road, in particular with respect to hazards related to traffic signs, roadside features, environmental risk factors, and road surface conditions. The objective of a road safety inspection is to identify traffic hazards and suggest measures to correct these hazards.

The World Road Association (PIARC) took the initiative to clarify the definitions and the procedures in an easy understandable way:

- **Road Safety Audits** (RSA) at the project design stage, before any construction has started, screen the designs on paper for any safety issues. This is a formal process best conducted by an independent auditor.
- **Road safety inspections** is driving and walking along the whole road, look at each road segment and check whether a series of items are consistent with road safety concerns. These inspections are usually repeated regularly.

B.2 The Re-Active Approaches

B.2.1 Black Spot Management (BSM)

Black spots are referred to as hazardous road locations, hot spots, or sites with promise. No standard definition exists of black spots. However, from a theoretical point of view, black spots should be identified as any location that has a higher expected number of crashes than other similar locations as a result of local risk factors.

In practice, black spots are identified in terms of the recorded number of crashes. Once black spots have been identified, crashes are analyzed in order to find a common pattern of crashes and factors contributing to them. A visit to each site identified is usually part of the analysis process. The objective of the analysis is to identify factors contributing to crashes that may be amendable to treatment. If a treatment believed to be effective is found, it should be implemented and its effects evaluated. The number of crashes before and after the implementation of the measure shall be collected for several years in order to correct for the regression-to-mean phenomena. Ideally, five years of before and after crash data are recommended to evaluate the true benefit of the treatment.

B.2.2 Network Safety Management (NSM)

In the last 5 to 10 years, several of the safest countries have supplemented or even replaced the traditional Black Spot Management (BSM) with Network Safety Management (NSM), which is identification and treatment of hazardous road sections.

Hazardous road sections have many names. Some of them are dangerous roads, black or red road sections, crash prone locations, or promising roads. No international standard definition of hazardous road section exists. A hazardous road section is any section between 2 and 10 kilometers that has higher number of severity of crashes than other similar road sections as a result of section based crash and injury risk factors. Like BSM, data about crashes, traffic volume, road design, and the surrounding environment are needed.

APPENDIX C

VALUE OF STATISTICAL LIFE IN ROAD SAFETY

Country	GDP/Capita, 2006 [1] ($)	VSL Low ($)	VSL Default ($)	VSL High ($)
Afghanistan, Rep. of.	264	15,840	18,480	21,120
Albania	2,892	173,517	202,436	231,355
Algeria	3,397	203,842	237,816	271,789
Angola	2,847	170,831	199,303	227,775
Antigua and Barbuda	12,203	732,169	854,197	976,225
Argentina	5,458	327,493	382,076	436,658
Armenia	1,882	112,921	131,741	150,561
Australia	36,442	2,186,544	2,550,968	2,915,392
Austria	39,190	2,351,412	2,743,314	3,135,215
Azerbaijan	2,469	148,148	172,840	197,531
Bahamas, The	18,961	1,137,674	1,327,287	1,516,899
Bahrain	21,123	1,267,383	1,478,613	1,689,843
Bangladesh	415	24,925	29,079	33,234
Barbados	12,523	751,380	876,610	1,001,839
Belarus	3,810	228,611	266,713	304,815
Belgium	37,614	2,256,822	2,632,959	3,009,096
Belize	4,030	241,793	282,092	322,391
Benin	624	37,433	43,672	49,911
Bhutan	1,437	86,241	100,615	114,988
Bolivia	1,167	70,023	81,693	93,363
Bosnia and Herzegovina	3,105	186,300	217,351	248,401
Botswana	7,021	421,262	491,473	561,683
Brazil	5,742	344,495	401,910	459,326
Brunei Darussalam	30,626	1,837,536	2,143,792	2,450,047
Bulgaria	4,120	247,173	288,369	329,564
Burkina Faso	456	27,383	31,947	36,511
Burundi	120	7,208	8,410	9,611
Cambodia	513	30,772	35,900	41,029
Cameroon	979	58,743	68,533	78,324
Canada	39,115	2,346,887	2,738,034	3,129,182
Cape Verde	2,425	145,472	169,717	193,963
Central African Republic	353	21,189	24,720	28,252
Chad	681	40,852	47,660	54,469
Chile	8,903	534,201	623,235	712,268
China	2,012	120,716	140,835	160,954
Colombia	2,911	174,632	203,737	232,842
Comoros	645	38,706	45,157	51,609
Congo, Democratic Republic of	147	8,792	10,257	11,723

Congo, Republic of	2,245	134,695	157,144	179,593
Costa Rica	5,173	310,378	362,107	413,837
Côte d'Ivoire	936	56,138	65,494	74,850
Croatia	9,666	579,937	676,593	773,249
Cyprus	23,779	1,426,729	1,664,517	1,902,305
Czech Republic	13,933	835,955	975,281	1,114,607
Denmark	50,904	3,054,232	3,563,270	4,072,309
Djibouti	1,030	61,791	72,089	82,388
Dominica	4,203	252,154	294,180	336,206
Dominican Republic	3,667	220,006	256,674	293,341
Ecuador	3,058	183,465	214,042	244,619
Egypt	1,489	89,317	104,203	119,089
El Salvador	2,661	159,646	186,254	212,862
Equatorial Guinea	7,315	438,886	512,034	585,182
Eritrea	267	16,014	18,683	21,352
Estonia	12,353	741,176	864,705	988,234
Ethiopia	202	12,123	14,143	16,164
Fiji	3,674	220,447	257,188	293,929
Finland	39,828	2,389,678	2,787,958	3,186,238
France	36,706	2,202,387	2,569,452	2,936,516
Gabon	6,836	410,135	478,491	546,847
Gambia, The	328	19,673	22,951	26,230
Georgia	1,764	105,845	123,486	141,127
Germany	35,433	2,125,965	2,480,292	2,834,619
Ghana	594	35,612	41,547	47,482
Greece	24,157	1,449,438	1,691,011	1,932,584
Grenada	5,293	317,592	370,524	423,456
Guatemala	2,327	139,593	162,858	186,123
Guinea	326	19,537	22,794	26,050
Guinea-Bissau	190	11,387	13,285	15,183
Guyana	1,170	70,205	81,906	93,606
Haiti	550	32,989	38,487	43,985
Honduras	1,462	87,744	102,368	116,992
Hong Kong SAR	27,499	1,649,932	1,924,921	2,199,910
Hungary	11,206	672,371	784,433	896,495
Iceland	54,205	3,252,313	3,794,365	4,336,418
India	792	47,503	55,420	63,338
Indonesia	1,641	98,458	114,868	131,277
Iran, Islamic Republic of	3,197	191,807	223,775	255,742
Ireland	51,800	3,108,004	3,626,005	4,144,006
Israel	20,177	1,210,635	1,412,408	1,614,181
Italy	31,802	1,908,098	2,226,114	2,544,130
Jamaica	3,887	233,207	272,074	310,942
Japan	34,264	2,055,819	2,398,456	2,741,092
Jordan	2,519	151,113	176,298	201,484

Kazakhstan	5,363	321,761	375,388	429,015
Kenya	670	40,215	46,917	53,620
Kiribati	658	39,461	46,037	52,614
Korea	18,395	1,103,720	1,287,674	1,471,627
Kuwait	31,014	1,860,857	2,170,999	2,481,142
Kyrgyz Republic	546	32,763	38,223	43,683
Lao People's Democratic Republic	573	34,398	40,132	45,865
Latvia	8,760	525,607	613,208	700,809
Lebanon	6,147	368,807	430,274	491,742
Lesotho	632	37,930	44,252	50,573
Liberia	171	10,253	11,962	13,671
Libya	8,327	499,639	582,913	666,186
Lithuania	8,768	526,083	613,764	701,444
Luxembourg	89,923	5,395,394	6,294,626	7,193,859
Macedonia, Former Yugoslav Republic of	3,102	186,116	217,136	248,155
Madagascar	331	19,878	23,191	26,504
Malawi	241	14,468	16,879	19,290
Malaysia	5,914	354,854	413,996	473,138
Maldives	2,629	157,724	184,011	210,298
Mali	487	29,217	34,086	38,956
Malta	15,716	942,954	1,100,113	1,257,272
Mauritania	938	56,281	65,661	75,041
Mauritius	5,043	302,560	352,986	403,413
Mexico	8,060	483,593	564,192	644,790
Moldova	991	59,472	69,385	79,297
Mongolia	1,216	72,971	85,133	97,295
Montenegro, Republic of	3,873	232,380	271,110	309,840
Morocco	2,149	128,935	150,424	171,913
Mozambique	338	20,285	23,666	27,047
Myanmar	232	13,935	16,257	18,580
Namibia	3,389	203,338	237,228	271,117
Nepal	376	22,547	26,305	30,063
Netherlands	41,046	2,462,772	2,873,234	3,283,695
New Zealand	25,129	1,507,719	1,759,006	2,010,292
Nicaragua	896	53,733	62,689	71,644
Niger	277	16,597	19,363	22,129
Nigeria	1,049	62,951	73,443	83,934
Norway	72,768	4,366,088	5,093,769	5,821,450
Oman	14,032	841,896	982,212	1,122,528
Pakistan	817	49,036	57,208	65,381
Panama	5,217	313,023	365,194	417,364
Papua New Guinea	943	56,594	66,027	75,459
Paraguay	1,657	99,391	115,956	132,521
Peru	3,366	201,940	235,596	269,253

Philippines	1,352	81,103	94,620	108,137
Poland	8,959	537,566	627,160	716,755
Portugal	18,418	1,105,096	1,289,279	1,473,461
Qatar	62,914	3,774,863	4,404,007	5,033,151
Romania	5,668	340,087	396,768	453,450
Russia	6,923	415,408	484,642	553,877
Rwanda	312	18,699	21,815	24,932
Samoa	1,990	119,426	139,331	159,235
São Tomé and Príncipe	769	46,125	53,812	61,500
Saudi Arabia	14,733	884,007	1,031,342	1,178,677
Senegal	768	46,062	53,739	61,416
Serbia	4,271	256,259	298,968	341,678
Seychelles	9,366	561,964	655,625	749,286
Sierra Leone	254	15,264	17,808	20,352
Singapore	31,028	1,861,673	2,171,952	2,482,231
Slovak Republic	10,357	621,425	724,995	828,566
Slovenia	19,021	1,141,283	1,331,497	1,521,710
Solomon Islands	661	39,680	46,294	52,907
South Africa	5,418	325,108	379,292	433,477
Spain	27,951	1,677,035	1,956,541	2,236,047
Sri Lanka	1,364	81,816	95,453	109,089
St. Kitts and Nevis	9,723	583,403	680,636	777,870
St. Lucia	5,546	332,779	388,242	443,706
St. Vincent and the Grenadines	4,695	281,720	328,673	375,627
Sudan	1,005	60,303	70,354	80,404
Suriname	4,136	248,162	289,522	330,882
Swaziland	2,431	145,862	170,173	194,483
Sweden	43,190	2,591,427	3,023,332	3,455,236
Switzerland	53,245	3,194,687	3,727,135	4,259,583
Syrian Arab Republic	1,844	110,615	129,050	147,486
Taiwan Province of China	15,978	958,652	1,118,427	1,278,203
Tajikistan	441	26,435	30,840	35,246
Tanzania	372	22,300	26,017	29,734
Thailand	3,166	189,984	221,648	253,312
Timor-Leste, Dem. Rep. of	348	20,879	24,359	27,839
Togo	352	21,145	24,669	28,193
Tonga	2,181	130,887	152,701	174,515
Trinidad and Tobago	13,996	839,779	979,742	1,119,705
Tunisia	3,044	182,629	213,067	243,505
Turkey	7,760	465,577	543,173	620,769
Turkmenistan	4,280	256,790	299,588	342,387
Uganda	318	19,084	22,265	25,445
Ukraine	2,291	137,480	160,393	183,306
United Arab Emirates	38,613	2,316,805	2,702,940	3,089,074
United Kingdom	39,681	2,380,853	2,777,662	3,174,470

United States	44,118	2,647,080	3,088,261	3,529,441
Uruguay	6,036	362,167	422,529	482,890
Uzbekistan	631	37,864	44,175	50,485
Vanuatu	1,851	111,052	129,561	148,069
Venezuela	6,834	410,054	478,397	546,739
Vietnam	723	43,361	50,588	57,815
Yemen, Republic of	884	53,019	61,855	70,692
Zambia	917	55,045	64,219	73,393
Zimbabwe	123	7,352	8,577	9,802

1. GDP /Capita 2006 Figures Based on the World Economic Outlook Database, International Monetary Fund, April 2008.