Roads

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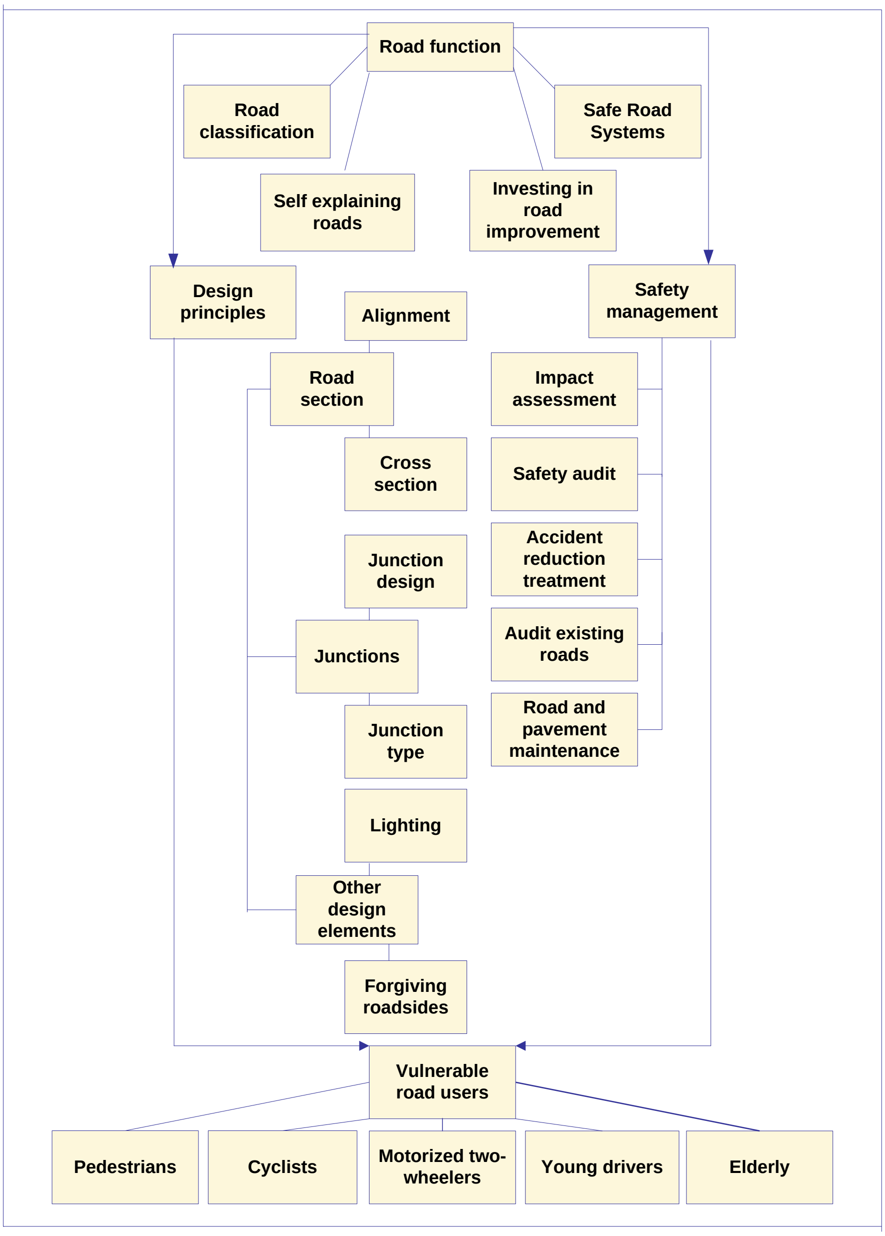
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Roads: a key Safe System strategy

The safe planning, design, operation and use of the road network is a key intervention strategy in the recommended Safe System approach to managing for better road safety results. See ERSO Road Safety Management web text.

Designing for road function

Roads should be designed to cater for a defined function, separating roads for through traffic, roads for distribution of traffic within an area, and local access roads. A *Safe System* needs vehicle design, highway design, the emergency medical system and road user behaviour to work together to avoid fatal and severe injuries. Road infrastructure should be designed taking account of the same injury tolerance criteria as those developed for vehicle occupant protection and pedestrian impacts, so that roads and vehicles together provide an effective safety system. By using “self-explaining road” principles, either through adopting a consistent and clearly differentiated design for each function group, or by removing unexpected higher risk sites, driver’s subjective assessment of risk can be improved. Zero fatalities and severe injuries is the long-term vision but physical measures may not be practical for all roads in the short-term, and investment priorities should be clearly established.

Urban roads

Urban safety management should define the function of each road, with safe speeds (30km/h) being applied on all residential access roads. Where a single road function cannot be easily established, space should be divided between the competing demands of the different users, sharing the priority between pedestrians, cyclists and vehicular users.

Rural roads

There are similar well established rural safety management processes. As traffic volumes increase, management of motorways using dynamic speed limits and additional peak hour running lanes can produce increased capacity without sacrificing safety.

Getting initial safety design principles right

Crash rates and injury outcome vary with road alignment, road width, roadside and median treatment, and with choice of junction type and design. Appropriate design choices are needed for roads serving each function to minimize the number of crashes likely to occur and to mitigate injury severity, particularly on higher speed roads.

Management processes

Safety management should start with a safety impact assessment before a decision is made to site a new road. Safety audit at the design and construction stage is needed to ensure all aspects of detailed design that might affect safety are addressed. Once the road is built, highway authorities have a responsibility to ensure its safe operation. This is best done through a combination of crash investigation and on-road inspection to enable cost effective remedial programmes to be developed; many tools exist to support these activities. Where reliable crash injury data is not available, road assessment programmes play an important role in helping to identify investment priorities.

Casualty reduction programmes

In the early stages of casualty reduction programmes, it may be most productive to deal with individual problem sites and sections. There are many established tools for this but these have limitations both in accurate risk assessment and achieving effective treatment across the whole network. Broader network management programmes, aimed at developing towards a *Safe System*, are recommended by international organisations such as the World Bank and OECD.

Management safe road operation

Ensuring speed limits are set at levels consistent with the function and design of the road is important in achieving a *Safe System*. The role of speed in road safety is now well understood and enforcement strategies can be deployed effectively where drivers flout speed regulations. Skid resistance of a road surface is an important road safety factor; with both micro-texture and macro-texture of the surface playing a part, so surface condition should be maintained to appropriate standards. High priority should be given to the safety of those working on the road network.

Roads need to cater safely for all users

The design of roads should be adapted to the limitations of human capacity. The biomechanical thresholds for serious and fatal injury are well-established. Among pedestrians the young and the elderly are most at risk. Risk to cyclists varies substantially between countries mainly reflecting the infrastructure provided for them and the motorized traffic levels they interact with. Risk for motorized two wheelers is particularly high and solutions are needed to minimize the severity of injuries resulting from their impact with roadside furniture. Road designers should recognize the diminished physical and cognitive capabilities of elderly road users.

eSafety and road infrastructure

Intelligent infrastructure includes the road network, its sensors, traffic information centres, vehicle, and the communication networks linking these components. Experiments are being pursued in each of these areas with the objective of developing effective co-operative vehicle-highway systems. There remain issues of accuracy, reliability and acceptability to be resolved and, at present, evidence of the safety benefits of practical co-operative systems remains limited. Where systems rely on recognising road markings and signs, these will need to be of an adequate quality. See ERSO eSafety web text.

See also Speeding web text for further coverage of these issues.

2 Designing for road function

2.1 Road classification

Roads should be designed to cater for a defined function. This typically reflects the distance of travel, level of traffic flow and desired speed of travel. Road networks in most countries will therefore reflect the development of a hierarchy of roads, with motorways at the highest level and local access roads at the lowest. In practice a basic hierarchy will occur naturally through the more heavily trafficked roads being engineered to higher standards. But it is important that the hierarchy is established to clear guidelines linking design to function, throughout the network. This is particularly necessary where different functional levels or different geographical areas are managed by different road authorities.

It is well established that managing roads and traffic to basic safety management principles in urban areas can produce overall crash reductions of at least 15% 9 (Dumas, 2000) even in well established networks. Applying area wide low speed limits can produce much greater reductions (3.1). There are also good examples of integrating safety management with other urban planning objectives (OECD, 1990). Similarly it is well established that most serious injury crashes on rural roads are associated with a small number of crash types which can be addressed by different aspects of engineering design (OECD, 1999).These crash types occur in different patterns on roads with different designs and speed limits (Lynam & Lawson, 2005).

At the simplest level, road function can be divided into three groups - arterial or through traffic flow routes, distributor roads, and access roads. These can be defined as (Wegman & Aarts, 2005)

Flow function: Roads with a flow function allow efficient throughput of (long distance) motorized traffic. All motorways and express roads as well as some urban ring roads have a flow function. The number of access and exit points is limited.

Area distributor function: Roads with an area distributor function allow entering and leaving residential areas, recreational areas, industrial zones, and rural settlements with scattered destinations. Junctions are for traffic exchange (allowing changes in direction etc.); road sections between junctions should facilitate traffic in flowing.

Access function: Roads with an access function allow actual access to properties alongside a road or street. Both junctions and the road sections between them are for traffic exchange.

The first two of these groups may be further subdivided into primary and local arterials and distributors, reflecting different flow levels within each group.

Roads are also often grouped by design “types”, i.e. motorways, other divided roads, 2-lane roads. Whilst motorways will always cater for a flow function, the other road types are often not used consistently to reflect a particular function, and designs within the road type groups can vary considerably. On average there are large differences in crash rate (both per km and per vehicle km) on the different road types (Lynam & Lawson, 2005), and thus national crash rates can be reduced by ensuring drivers use the most appropriate road for their trip purpose, and that the road design is optimized for its function.

The match between driver behaviour and road design will be optimized where the road design gives a clear message to the road user of the function of the road, and the hazards that are likely to be encountered.

The high proportion of traffic on motorways in the Netherlands influences road fatality rates.

An intensive period of motorway building during 1970s and 1980s in the Netherlands has resulted in 40% of the national total of vehicle kilometres being travelled on motorways, which have low fatality rates compared with other rural roads, compared with 20% in Britain and 14% in Sweden. This high usage is encouraged by both the high density of the motorway network and the high population density. The density of motorway network in the Netherlands is four times that in Britain and 18 times that in Sweden. Population density in the Netherlands is, on average, about 60% higher than in Britain and almost 20 times that in Sweden.

Source: Koornstra et al., 2002

Although the same general functional management principles need to be applied for both urban and rural road networks, the detailed functions that need to be served differ, and the mix of traffic differs. Thus the way in which each function is translated into design also differs (sections 3 and 4).

Current crash databases reflect the road classifications used by the crash record forms in each country. International databases, such as IRTAD, provide comparable data on more generic road type groupings (motorways, A Class non-urban roads, etc), but the design of roads within these groups varies between countries.

2.2 Safe System

Over the last decade, the concept of *Safe System* has been developed, expanding from the Swedish *Vision Zero* and the Dutch concepts of *Sustainable Safety* into an approach supported in various forms in many countries and recommended by the OECD and other international organizations (National Co-operative Highway Research Program, 2008, OECD, 2008). The European Commission has recently proposed that the EU should target the virtual elimination of deaths by 2050 with an interim target to 2020 (European Commission, 2011). At its broadest the concept includes vehicle safety, highway safety and road user behaviour initiatives, but the over-riding focus is the creation of a system in which the different measures work together to create an environment within which the chance of fatal and serious injury outcomes, if impacts occur either in collisions between road users or in single vehicle crashes, is minimal. The focus of *Safe System* is on fatal and serious injury prevention rather than crash prevention in general which has implications for selecting intervention.

A large body of research shows the speeds and vehicle design criteria needed to keep injury severity within tolerable levels for car occupants in car to car collisions and for pedestrians impacted by cars (ERSO: Vehicle Safety and Speed text). Similar criteria can be used to align the protective design of a road to minimize severe impacts between cars and roadside objects, or to limit the possibility of higher speed vehicle to vehicle impacts through median and junction design (Tingvall & Haworth, 1999; Lynam et al., 2004). There is not yet sufficient knowledge to define speeds and infrastructure design that would result in tolerable injury severity for motorized two-wheelers or from impacts between cars and heavy good vehicles.

Measures to minimize injury severity to occupants of vehicles leaving the road include creation of clear zones alongside roads, use of passively safe materials or shielding of objects where impact would involve higher energy levels than those leading to tolerable injury levels (ETSC, 1998). Severe injury through impacts between opposing traffic flows can be avoided by using median or barriers, while severe injuries at junctions can be reduced by only allowing vehicles to merge at speeds and angles that ensure low relative impact speeds. These are discussed in more detail in section 5.

The Swedish concept of "safe speed"

Tingvall and Haworth (1999) proposed that the driver/vehicle/road system should operate in a way that, in the event of an impact, forces are not exerted on vehicle occupants or other road users which are likely to lead to a fatality. Thus, where pedestrians are present, vehicle speeds should be no higher than 30km/h. Where vehicle to vehicle impacts occur they should be at speeds below the impact speeds at which cars can be shown (through the European New Car Assessment Programme) to safeguard occupant life. These principles typically lead to the following "safe speeds".

Road type/traffic situation	Safe speed (km/h)
Roads with potential conflicts between cars and unprotected road users	30
Junctions with potential side impacts between cars	50
Roads with potential head-on conflicts between cars	70
Roads where head-on and side impacts with other road users are impossible	> 100

In Sweden, the concept of a safe speed has been adopted as a basis for considering appropriate speed limits. Ratings are being developed through the European Road Assessment Programme showing how well the road is designed to ensure forces involved in impact with road infrastructure also keep within the same thresholds, and a new speed limit based on these principles is now gradually being introduced in Sweden.

Source: Tingvall and Haworth,1999.

The Dutch vision of Sustainable Safety.

This policy was launched at the beginning of the 1990s and accepted as a formal part of Dutch policies in the mid 1990s.

"The Sustainable Safety vision is based on two leading ideas: how to prevent human errors as far as possible, and how to ensure that the crash conditions are such that the human tolerance is not exceeded and severe injury is practically excluded. The starting point of 'sustainable safety' was to drastically reduce the probability of crashes in advance through safety conscious planning and design. Where traffic crashes still occur, the process that determines the severity of these crashes should be influenced, so that serious injury is virtually excluded. Within sustainable safety, man is the reference standard (human error and human tolerance). A sustainable safe traffic system has an infrastructure that is adapted to the capabilities and limitations of humans through proper planning and road design, has vehicles that are equipped to simplify the driving task and offer protection to the vulnerable human being (crash protection), and finally, has road users that are properly educated and informed, and whose driving behaviour is regularly controlled. The key-issue of 'sustainable safety' is that it has a preventative rather than a curative (reactive) nature."

The updated Dutch Sustainable Safety vision presents the requirements with regard to maximum speeds in different traffic situations that follow the safe speeds proposed by Tingvall and Haworth. To the three original principles of functionality, homogeneity and predictability have been added forgivingness (of the environment and of road users) and State awareness (the road user’s ability to assess their own task capability).

Source: Wegman et al. (2005), Wegman and Aarts, 2005 (page 14; translated from Dutch)
Wegman, Aarts and Bax (2008) Advancing Sustainable Safety
Weijermans and Schagen, van (2009) Ten years of Sustainable Safety

2.3 Self-explaining roads

The concept of *self-explaining roads* on which the driver is encouraged to naturally adopt behaviour consistent with design and function originated in the Netherlands (Theeuwsen, 1998; Master, 1998). The aim is that different classes of roads should be distinctive, and within in each class features such as width of carriageway, road markings, signing, and use of street lighting would be consistent throughout the route. Drivers would perceive the type of road and “instinctively” know how to behave. The environment effectively provides a “label” for the particular type of road and there would thus be less need for separate traffic control devices such as additional traffic signs to regulate traffic behaviour. The primary focus is to reduce crash likelihood but achieving speeds appropriate to the environment should also minimize crash severity. Early assessments using picture-based tests with clear design features showed for example that this enables drivers to better categorise roads (and associate appropriate speeds with them) and that signs in unexpected places take longer to identify.

The following features have been suggested by Dutch researchers as relevant for promoting recognition of *self explaining roads* (RIPCORD-iSerest, Report D2.1, 2008 - longitudinal marking, driving direction separation, lane width, adjacent cycle lanes, road surface, shoulder characteristics (width, obstacle distance, reflector posts) road side environment, intersections and transitions. Work has continued in the Netherlands (Aarts & Davidse, 2007; McDonald & Li, 2006) to investigate how different element within a “sustainable” road network can advance its recognisability. “Readability” has been added to the key concepts in Advancing Sustainable Safety (Wegman et al., 2008).

This approach to the concept uses simplicity and consistency of design to reduce driver stress and driver error. It is already used for the highest road classes (motorways) but on low class roads consistency in design is often compromised by other objectives such as high access levels, variable alignment, mixed use and variable roadside development, which result in lack of consistency and lack of differentiation between road classes. Different countries have different systems of road hierarchies and different speed limits on them. In some situations, uncertainty can be a benefit leading to greater care (eg mini-roundabouts). Thus it is not always possible to create fully consistent designs within a given road type. Interpretations of *self explaining roads* in some other countries have focused more on intuitive and understandable design. Although consistency of design and driver expectation can be an important part of this, it is equally important to clearly identify locations where risk may be higher than at adjacent sites along the same roadway; in Britain this is done as part of route management studies (Institution of Highways and Transportation, 2007).

Both interpretations of the concept place a strong emphasis on encouraging appropriate speed choice. Measures associated with the broader interpretation of the concept include various forms of psychological traffic calming, including curve treatments, village entrance treatments, removal of road markings, and road and lane narrowings. But more specific warning indicators may also be necessary, which would not necessarily have been expected in the original concept. “Roadside vegetation, marker posts and other elements on shoulder like curve warning signs and guardrails underline the appearance of the road. When applied correctly, driver’s concentration can be raised and driving speed reduced by the design of the roadside” (RIPCord-iSEREST, D13, 2008). In some cases, drivers may not appreciate the true risk simply from visual clues (eg drivers often overestimate the risk of motorways and underestimate the risk on 2-lane rural roads) so road users need a correct understanding of risk before visual clues alone will be fully effective.

Despite the strong intuitive benefits, to date actual evidence on the effectiveness of *self explaining road* principles on behaviour is scarce and mainly shows more homogenous speed choice.

2.4 Investing in road improvement

The returns from low-cost engineering measures have generally been justified in terms of the first year rate of return by comparing the value of crash savings in that year with the cost of the treatment. Crash savings are so high (ETSC, 1996) that more detailed analyses are not necessary. However, the safety engineering focus increasingly is on proactive as opposed to reactive approaches to road improvement assisted by road assessment programmes to identify affordable improvements. (UNRSC,2011, OECD, 2008).

As the safety of the network is improved and the most cost-effective measures have already been applied, more detailed cost-benefit assessments are required, ideally taking into account investigation and redesign costs as well as engineering costs of the new measures. Advice is given in PIARC (2003) on techniques to be followed.

For longer-life measures, such as the construction of safety barriers, net value costs (construction and maintenance costs) and net value of the benefits from estimated crash reduction discounted over the life of the project should be compared.

Risk on any specific road can be defined in terms of risk to each individual driver using the road (crashes per vehicle km) or of collective risk of all drivers using the road (risk per km). High-flow roads will have low individual risks but high collective risk. Investment to reduce crashes on high-flow roads is more likely to be justified than investment on low-flow roads because a larger number of drivers benefit. Investment in crash reduction is still likely to be worthwhile on those low -flow roads where individual risk is significantly higher than average for these roads.

Design standards and remedial programmes need to consider both risk to the individual driver and collective or societal risk (i.e. total risk to all road users). The former is implicit in many design standards (eg by stating the width of roadside clear zone below which objects must be protected). The latter is reflected in cost-benefit or cost-effective assessments (PIARC, 2003) which are used in deciding how to use the available budget to provide the highest safety return, in economic terms. An example of a process by which network wide crash costs can be used to identify roads on which potential improvements would be worthwhile is given in (BASt) – see section 7.2. The EuroRAP programme (see section 4) provides a basis by which roads having high numbers of fatal and serious crashes compared with expected numbers for that road type can be identified within national rural road networks. On these roads, either physical design changes are needed or speed limits lowered to compensate for the inconsistency with the present design in line with *Safe System* principles.

3 Urban roads

3.1 Urban Safety Management

Factors that need to be taken into account in urban areas include:

- High density both of traffic and of other functions being served by the road
- Integration of traffic into residential space
- Catering for the needs of a wide range of road users using different modes

Crashes in residential areas are characterized by larger proportions of crashes involving children and the elderly and crash locations scattered widely rather than concentrated at individual problem sites (high-risk sites) OECD (1979). The majority of the crashes are likely to occur on roads that serve a distributive function within these areas, and the road layout plays an important part in the intensity of crash risk, with absolute number of crashes being higher in older layouts

Area-wide measures are therefore necessary for the design and implementation of countermeasures. Measures must not only address crash injury reduction, but should also take into account in resident's satisfaction with the area within which they are living. Early involvement of the community in the decision making process is important if this is to be achieved.

Planning principles for new residential areas should, where possible, include:

- Differentiation of streets according to their function
- Distribution of traffic into a residential area from a ring road rather than central distribution
- Cul-de-sac streets or short lengths divided by speed-reducing measures
- Housing which accesses onto the access streets rather than the distributor streets

Although such layouts cannot be applied in full to the modification of existing street patterns, the same principles are equally applicable.

The safe speed (2.2) for areas where pedestrians interact with vehicles is 30 m/h (20 mph). Zones with 30km/h speed limits have been widely established, initially in the Netherlands and Germany, but subsequently in many other countries. Some evaluations have recorded casualty reductions of up to 60% although the changes can be smaller depending on the physical changes used, and 25% is a more typical average reduction (Elvik et al., 2009). These zones also have a positive effect on the quality of life, with less noise, lower emissions, and easier road crossing, but they can cause some delay for buses and service and emergency vehicles that need to use them. Areas with similar lower limits but without vertical speed-reducing measures have been trialled. With strong local community support and well-engineered layouts, these can also achieve lower speeds and better quality of life, but they are not as effective as zones with fully engineered speed reduction measures.

30km/h zones

Since 1983 it has been legally possible to set up a 30km/h zone in the Netherlands. These are used in residential areas which have living, shopping or work functions. By 2007 about 70% of the total length of residential roads had been converted to Zone30. Initially speed reducing measures such as speed humps and narrowings were used extensively within these areas to ensure drivers complied with the speed limit. More recently zones are to a lower cost design to enable more zones to be completed, and speed reducing measures are confined to “dangerous” sites. Speeds are higher than 30 km/h on some road sections but speed reducing measures ensure lower speeds at intersections. “Classic” speed humps are the most effective speed reduction measure; they are often criticized but there is currently no good alternative measure. Under Sustainable Safety guidelines, there should be no through traffic within these zones; SWOV recommends zones are no larger than 1 kilmetre to ensure that traffic volumes on surrounding distributor roads remain low enough to retain reasonable crossing opportunities for pedestrians and cyclists on these roads.

Source: SWOV Fact Sheet Zones 30: urban residential areas 2009

Urban Safety Management in UK

Principles adopted for effective urban safety management in UK include

- Consider all kinds of road user especially the most vulnerable
- Consider the functions and use of different kinds of road
- Formulate a safety strategy for the area as a whole
- Integrate existing crash reduction efforts into the safety strategy
- Relate safety objectives to other objectives for the urban area
- Encourage all professional groups to help achieve safety objectives
- Guard against adverse effects of other programmes upon safety
- Use the scarce expertise of road safety professionals effectively
- Translate strategy and objectives into local area-wide safety schemes
- Monitor progress towards safety objectives
- Four steps in defining functions and objectives are
- Identify current road hierarchy
- Appraise extent and characteristics of crashes and public perception of safety on all parts of the network
- Assess traffic flow and performance on each route in relation to the functions expected from its role in the hierarchy
- Set safety objectives for each part of the road network

Source: IHT (1990b), Department for Transport (2003)

The wide range of social and environmental objectives leading to improvement of urban areas means that integrated traffic safety management is important (OECD, 1990). In addition to playing a leading role where traffic safety is the primary stimulus for a scheme, traffic safety experts need also to seek opportunities to improve safety where other objectives provide the main basis for change. The emergence of good integrated schemes is usually heavily dependent on significant national or regional involvement, or on strong local political will.

Urban safety management programmes are expensive and involve engineering works over a large area. Good co-ordination and management and extensive involvement of local representatives are therefore essential to successful implementation (EC, 2001).

The European Commission DUMAS project

The DUMAS project was established with partners from 9 European countries to encourage the wider use of urban safety management principles. The DUMAS Design Framework defines potential interactions in order to make urban designers, planners and engineers more aware of the effect of their strategies on others. A joint vision for the urban area and strong political leadership are required. Examples are provided of the management structures that might be developed and the consultation processes likely to be necessary. The key principles of managing traffic to achieve a safer distribution, and managing speed to achieve a safer circulation emphasize the need for a clear functional hierarchy linked to a speed management strategy for the whole urban area.

Source: European Commission, 2001; Department for Transport, 2003

3.2 Shared Space and Mixed Priority

In most urban streets there is competing demand for space between different road users (drivers, riders, pedestrians, cyclists, traders). Roads with a strong flow function can only effectively meet that function by reserving a large part of the space for vehicular movement. But in roads with less focus on motor vehicle traffic flow, and where relatively low speeds are desired because of dangerous mixed use, non-vehicular users can claim larger proportions of the road space. Greater non-vehicular activity leads in turn to drivers recognising the more mixed function of the road, and this can lead to lower speeds.

Features which emphasise this mixed function include traffic calming measures such as varying road width and reducing driver sight-lines by chicanes or environmental planting, pavement extensions and angled parking. Measures which purposely remove the clear separation between drivers and other road users (such as removal of pedestrian guard rails, signs, markings) can also be used to discourage the concept of vehicular dominance, and at the same time can produce better visual environments. The most extreme such measure is the creation of a common surface within which both vehicles and pedestrians can move, ideally using a surface (e.g. block paving) which neither group see as obviously giving them priority. Such a design has been utilised for many years in areas providing very local vehicular access, such as *Woonerven*. New residential housing can also be designed around pedestrian movement and building lay-out, rather than starting with a defined vehicular street layout. More recently the shared space approach has also been tried in roads with rather higher vehicle speeds and flows, with no clear priority at junctions, but as yet there is little hard evidence of its effect on safety. The needs of public service and emergency vehicles always need to be taken into account.

The concept of mixed use goes beyond these “shared space” examples, with other objectives such as economic strength and better community interaction being pursued. Experiments on UK roads (Department of Transport (GB), 2008) suggest that each scheme needs to be tailored to the particular problems of the local area. Rather than general use of shared space, the schemes encourage the use of informal crossing (sometimes diagonal) and seek to ensure reduced speeds through vertical and horizontal deflection of vehicle paths. Evaluation of such schemes typically gives much weight to environmental quality, pedestrian and cyclist movement, and changes to the local economy, but some improvement in safety often seems to be one benefit.

4. Rural roads

4.1 Rural Safety Management

A network of higher quality interurban roads is required in every country to ensure the safe and efficient transit of people and goods. Part of this network is usually provided by motorway standard roads, supplemented by other divided, restricted access roads (called express roads in some countries). The standard of this latter group varies between and within countries. High interurban flows are also carried on 2-lane roads in some countries, although these are more suited to local rural roads.

Average fatal crash rates per vehicle kilometre can be up to six times higher on 2 lane rural roads than on motorways, and decrease as traffic flows increase (Lynam et al., 2004 The density of severe (fatal and serious injury) crashes per kilometre is typically greatest for divided carriageways below motorway standard, but less than twice that on motorways or 2 lane roads. Eighty per cent of all fatal crashes on major inter-urban roads occur due to single vehicles leaving the road, impacts at junctions, head-on impacts with opposing vehicles or impacts involving vulnerable road users (OECD, 1999; Lynam, 2003). The proportion within each of the four groups varies between countries depending on the characteristics of their road network and the traffic flow levels. The proportion also varies between road types, and at different flow levels (Lynam & Lawson, 2005).

Motorway capacity can be safely improved through active traffic management (4.2). Information on management processes and development of crash reduction programmes for the improvement of general purpose roads is given in sections 6 and 7. The long-term objective should be to modify design and road user behaviour to achieve the *Safe System* principles described in section 2. Lower flow rural roads where crashes are unlikely to be clustered can still benefit from self-explaining measures; these may not be so self-explaining when first encountered so appropriate behaviour will have to be learnt, but they could lead to substantial changes to the perceived characteristics of rural roads (RIPCORD-iSEREST, Report D13, 2008).

The European Union has published guidelines for the design and management of the Trans European Network, and an Infrastructure Directive (European Commission, 2008) which is mandatory for roads on that network and suggested as good practice for all roads. Several European research projects (SAFESTAR) have developed advice on design standards for interurban rural roads.

European Road Assessment Programme (EuroRAP)

The European Road Assessment Programme was developed as a star rating system to complement the vehicle assessment programme NCAP (ERSO: Vehicle Safety and Safety Ratings web rexts). It ranks roads on the basis of their risk to individual drivers, using a scoring system based on the extent to which the design of the road reduces the chance of fatal or severe crashes in the four main categories described in 4.1. This follows the *Safe System* approach by using vehicle speed, and its role in the injury outcome of both vehicle-vehicle impacts and vehicle infrastructure impacts, as a key factor in this assessment. By also mapping crash density, EuroRAP is able to show both where the risks are high to individual drivers and where collective risk is high due to high traffic volumes. Thus instead of just identifying sites with high numbers of crashes as a focus for treatment within a fixed budget, an assessment can be made of the investment required to bring risk down to defined levels on different road types. (Castle et al., 2007). This can be used both to develop programmes towards long-term goals to eliminate deaths and serious injuries and to demonstrate priorities in the investment timescale of such programmes.

The second part of the EuroRAP toolbox is a Road Protection Score (RPS) which is based on visual inspection of all the major roads within a network. This enables potential high risk sections to be identified through observing clear deficiencies in the design of injury protection features on specific road sections. High-risk road sections identified through crash histories will not necessarily be the same as those identified through visual inspection, partly because of the random nature of crash occurrence particularly where crash frequencies are relatively low, but comparisons have shown there is a strong link between the two (Castle et al., 2007). The two sources of data within EuroRAP thus complement each other. A large number of European countries are now undertaking EuroRAP surveys, and similar assessments have been developed in Australasia and the USA. In Australia, the assessment has been extended to include deficiencies in primary safety – i.e. the likelihood of an crash occurring as well as the likely injury outcome. Using these ideas, the International Road Assessment Programme (iRAP)has been developed (IRAP, 2009) which is now being deployed in a substantial number of low and middle income countries. This has developed the RPS scoring into a model which estimates severe injury crash rates and proposes improvement programmes

Source: Lynam et al. (2007) EuroRAP II Technical Report (2005-6), www.eurorap.org
Lynam, D. (2012) Development of risk models for the Road Assessment Programme, TRL Report CPR1293 (also available as iRAP report RAP504.12)

4.2 Managed motorways

Managed motorways have two main elements – variable (dynamic) speed limits (VSL) and hard shoulder running. They typically involve overhead gantries, lane-specific signals and driver information systems (Highways Agency Managed Motorways). At appropriate sites, they can provide a lower cost option to widening motorways.

VSL require computer based calculation of the most appropriate speed limit at any time based on traffic volume and vehicle spacing. The measure aims to smooth traffic flow when motorways are congested, as a result of heavy flows or incidents ahead. In Britain for example, results of evaluation of a Motorway Incident Detection and Automatic Signalling system showed that after detecting the presence of stationary traffic on a motorway, setting a signal with an advisory 50mph speed limit resulted in a net reduction of 18% in personal injury crashes.

Hard shoulder running is a means of providing additional traffic lane during periods of congestion. The need to ensure that safety is not compromised by the loss of the hard shoulder means that lower speed limits are required while this lane is in operation. Trials in GB initially used speed limits of 50mph (compared to the limit of 70mph for normal running) – but this has subsequently been increased to 60mph (Highways Agency Managed Motorways). Dutch rush hour lanes typically have speed limits set at least 20 km/h lower than the normal limit (In 't Veld, 2009). In GB, emergency refuge areas are provided at 800 metre intervals beside the hard shoulder running lane and a roadside telephone link is provided to the Regional Control Centre. Signs and signals are used on managed motorways to inform drivers of traffic conditions ahead, speed limits and availability of lanes.

Initial assessments of managed motorway trials (Highways Agency Managed Motorways), (In 't Veld, 2009) shows reduced emissions, lower fuel consumption, and better journey predictability while also suggesting that safety has not been compromised and that injury crash rates may have decreased.

5 Getting initial safety design principles right

Road safety analysis has contributed to the international experience on identifying relationships among various road design elements and crash risk, and best practices towards improving road safety. In the following paragraphs, road safety issues related to road characteristics and road infrastructure features are discussed. The issues presented are based on a synthesis of the international literature. It should be noted that the following sections are a synopsis of the international experience and practice, and they are not exhaustive on the effect of road design elements on road safety.

Many of the basic principles for good road design were developed up to 40 years ago, and are still valid today. A range of technologies are being tested which may lead to useful future developments. Further safety engineering refinements have been explored in demonstration programmes to ascertain casualty savings and benefits and costs and demonstrably effective measures are being rolled out. Good summaries of existing knowledge on the effectiveness of highway safety measures are provided by Elvik et al. (2009), Nation Co-operative Highway Research Program (2008), RIPCORD-iSEREST, Report D13 (2008), Lamm et al. (1999), Ogden (1996), UNRSC (2011), iRAP Road Safety Toolkit (2010).

Road design optimization aims at the selection of geometric design parameters resulting in a road environment that is "non-surprising", in the sense that users are not faced with unexpected situations, as well as "forgiving", in the sense that users' mistakes can be, if not avoided, corrected. The selected design speed, on which road alignment parameters are determined, needs to be realistic and compatible to the expected operational speed. Moreover, the design speed should be in accordance to the type and functional requirements of the road, and compatible to the roadway environment.

In the following paragraphs, various road design elements are examined and assessed, including horizontal and vertical alignment and their combination, as well as cross-sections characteristics.

5.1 Alignment

The horizontal alignment of a road comprises straight lines, circular curves (with a constant radius), and transition curves, whose radius changes regularly to allow for a gradual transfer between adjacent road segments with different curve radii. Various sequences of these three basic components are possible. The main objective of horizontal alignment should be to ensure consistency and uniformity along the alignment, in order to avoid the creation of sections demanding an important adjustment of travel speed. In general, uniformity on the alignment is achieved by avoiding steep changes of alignment features.

Estimating the crash risk in horizontal curves

Several studies have been conducted to estimate the crash risk in horizontal curves. Their main conclusions are:

- The crash rate in curves is 1.5 to 4 times higher than in tangents (i.e. straight sections) (Zeeger et al., 1992)
- 25 to 30% of all fatal crashes occur in curves (Lamm et al., 1999)
- Secondary rural roads, which are built following lower design standards (including more and sharper horizontal curves) have on average a higher proportion of crashes in curves (SETRA, 1992)
- Approximately 60% of all crashes occurring in horizontal curves are single-vehicle off-road crashes (Lamm et al., 1999)
- The proportion of crashes on wet surfaces is high in horizontal curves
- Crashes occur primarily at both ends of curves. Council (1998) notes that in 62% of fatalities and 49% of other crashes occurring in curves, the first manoeuvre that led to the crash was made at the beginning or the end of the curve.

On horizontal curves, because of the limited sight distance and the increased probability of skidding, increased crash rates are observed. The majority of crashes on horizontal curves concern single vehicle run-off crashes and head-on collisions (Torbic, 2003).

Horizontal curves of low radii lead to road safety problems. Research results show that the number of road crashes tends to increase when the radii of horizontal curves decreases (IHT, 1987; Hauer, 1999) increasing significantly for radii < 200 metres. Moreover, a large central angle (i.e. the angle subtended at the centre of the circular curve) is associated with sharp horizontal curves in having insufficient sight distance. To ensure a consistent design, designers should use small angles with sufficient sight distance (Al-Masaeid 1999).
The transition from a tangent (i.e. straight) section to a circular curve should be achieved by a transition curve, where the radius of curvature decreases linearly as a function of the arc length. When driving in this type of curve, the driver will follow the curve by turning the wheel at a constant rate in the direction of the curve. Consequently, the need for abrupt movements, in order to negotiate the curve, is eliminated (Elvik et al., 2009).

An important additional safety effect concerns the frequency of horizontal curves along the alignment. It has been shown that the presence of a single curve can be a risk factor, especially for low radii. If a sharp curve is located on a road with low average curvature (i.e. long preceding tangents), crash risk increases significantly (Hauer, 2000).

Horizontal alignment sequences should reduce operating speed variations along a route. A sharp (i.e. lower radius) curve after a long tangent or after a sequence of significantly more gentle (i.e. higher radius) curves may increase crash risk. The transition to sharper curves should therefore be carried out by a progressive reduction of radii along sequential curves, following the respective regulations on radius sequences (Bonneson, 2000; Seneviratne, 1994; Lamm et al., 1999).

Super-elevation is a road’s transverse incline toward the inside of a horizontal curve. It slightly reduces the friction needed to counter the centrifugal force and increases riding comfort. The maximum speed in a curve increases with superelevation. A transition zone between the tangent and the horizontal curve is needed to gradually introduce the superelevation Zeeger (1992) reports that improving the superelevation reduces the number of crashes by 5 to 10%.

On two-way two-lane roads, it is important to ensure sufficient length and sight distance for overtaking. It is recommended that values of curve radii, for which it is not clear whether there is possibility for overtaking, are avoided.

The vertical alignment of a road consists of straight segments (levelled or inclined) connected by sag or crest vertical curves. Combinations of these elements create various shapes of road profiles. The longitudinal section of a road includes sections with constant gradient and the related transition curves.

Estimating the crash risk in vertical curves

Several studies have been conducted to estimate the crash risk in vertical curves. Their main conclusions are:

- Crashes occur more frequently on gradients than on level sections. Crash frequency increases with gradient percent (Harwood et al., 2000)
- Crash frequency and severity are higher on downhill gradients than on uphill gradients, with a high involvement of heavy vehicles.
- The difference in height between the top and bottom of a slope is seen as a better indicator of crash risk than the gradient percentage (SETRA,1992)
- A horizontal curve radius will be perceived incorrectly if the curve overlaps with a crest or sag vertical curve (Hassan et al., 2002). In particular, the coincidence of a horizontal and a crest vertical curve may, under certain conditions, lead to significant limitation of the available sight distance and prevent the prompt perception of the curve. Accordingly, the coincidence of a horizontal and a sag vertical curve may create a false impression of the degree of curvature.

On sections with high gradient, safety problems may occur from speed differentials between passenger cars and heavy vehicles (e.g. heavy vehicles idling on upgrade sections), as well as vehicles braking on downhill sections (e.g. increases in braking distances and possibility of heavy vehicle brake overheating). It should be noted that road sections with gradients higher than 4% tend to present an increased road crash risk (Transport Department, 1993). Higher radius vertical curves have a smaller crash rate than lower radius vertical curves (Hauer, 1999).

An inefficient combination of horizontal and vertical alignment may lead to road safety problems, even when the horizontal and the vertical alignment are separately correct and according to guidelines. Poor coordination of horizontal and vertical alignments can create locations where the available sight distance drops below the required sight distance (Hassan & Easa, 2000). The coincidence of a horizontal and a sag vertical curve may create a false impression of the degree of curvature (i.e. the horizontal curve may seem to have a higher radius than the actual), and may contribute to increased crash rates (Smith & Lamm, 1993; IHT, 1990).

Increasing sight distances; sufficient sight distances are one of the basic factors of road safety design elements. However, in several studies it has been shown that increasing visibility may lead to an increase of the number of crashes, as the improved sight distance may cause higher speeds of vehicles.

Effectiveness of horizontal and vertical alignment elements

Improving the alignment and sight conditions of a road makes it easier to plan driving, because the path of the road and other road users are more easily visible. Another objective is to increase mobility, by improving horizontal and vertical curves as well as gradients, which lead to significant reductions in speed. A synthesis of the international experience, as presented in the "Handbook of Road Safety Measures" (Elvik et al 2009) suggests the following can lead to crash reductions:

- Increasing the radii of horizontal curves
- Constructing transition curves (clothoides)
- Reducing the proportion of road length which lies in sharp horizontal curves
- Reducing gradients

5.2 Cross-sections

Cross-sectional roadway elements include lane width, shoulder width, shoulder type, roadside features, median design, and others (Zeeger & Council, 1995).

Lane width should be examined in relation to the expected operational speed. Very narrow lanes cause problems, especially as far as heavy vehicles are concerned. In general, increasing lane width results to improved road safety, but very wide lanes may lead to increased travel speeds and encourage unsafe overtaking manoeuvres. Research results have shown that crash risk decreases when lane width increases. Results for two-lane roads indicated that increasing lane width beyond 3.3 metres may not be justified in terms of road safety benefit (IHT, 1990; Hauer, 1999).

The implementation of a shoulder (especially paved) or an emergency lane also contribute to improved road safety on interurban roads (Ogden, 1997). Research results indicate that very narrow shoulders (e.g. <0.5 metres), or very wide emergency lanes (e.g. >3 metres) which may end up being used by drivers as regular lanes in increased traffic, are related to increased crash rates (IHT, 1990). Crash risk decreases when shoulder width increases, but research results for two-lane roads indicated that increasing shoulder width beyond 2.5 metres may not be justified in terms of road safety benefit (Zeeger et al.,1987).

The construction of a median on interurban roads can contribute significantly in reducing the number and severity of road crashes. On roads with more than two lanes, the implementation of a median leads to significant reduction of the number of road crashes. However, crashes still occur, because of drivers crossing the median and entering the opposite traffic stream. The number of these crashes decreases when median width increases, although this effect varies with the speed of traffic on the road. For median width equal to 12 metres, only a small proportion of vehicles that enter the median are likely also to enter the opposite traffic stream, but some risk remains even up to widths of 20 metres.

On single carriageway roads (undivided roads), central hatching can be used to discourage overtaking and there is some evidence that central rumble strips reduce head-on collisions. On uphill sections, where heavy vehicles have low travel speeds, an additional lane for slow moving traffic can reduce risky overtaking. The locations where the road cross-section changes (including transition from dual to single carriageway road, reduction of the number of lanes, reduction of lanes/shoulders width etc.) are also considered to be critical for road safety. On these locations, satisfactory sight distance, sufficient transitory length and appropriate signalization are required. On tangent road sections in curves, the lack of appropriate cross-slope (superelevation) may increase crash risk, especially when combined with insufficient pavement skid resistance.

Cross-section improvements

Improving the cross-section of a road is intended to give all road users increased safety margins by making the road wider and separating the carriageways, and increase mobility by increasing the capacity of the road. Cross-section improvements include the following measures (Elvik et al., 2009):

- Increasing the number of traffic lanes; the measure should be primarily seen as a measure to increase road capacity mobility and it appears to lead to more crashes.
- Increasing road width; an increase leads to a reduction in the number of both injury and property damage crashes in rural areas. However, in urban areas, a corresponding increase of road width lead to an increase in the number of crashes.
- Increasing lane width; the measure appears to have the same effect on injury crashes as increasing the width of the road.
- Increasing shoulder width, which can also reduce the number of injury crashes, as long as the increase of shoulder width does not result to a significant decrease of lane width.
- Constructing a median; on four lane roads, the construction of medians reduces the number of crashes. However, medians on two-lane rural roads may increase the number of crashes.
- Increasing median width; in general, the measure results in crash reduction.

Source: Elvik et al., 2009

***Safe System* cross-sections vary with the speed of traffic**

For 120 km/h roads, central barriers are needed to ensure a *Safe System*, and these need to be high containment if cross-over of heavy vehicles is to be avoided. Even at 80 or 90 km/h, a median of 4 metre width may be needed to achieve a *Safe System*. At speeds of 70km/h or below, head-on impacts between cars can be tolerated with only a small risk of severe injury to belted occupants.

5.3 Junctions

Junctions, at-grade or grade separated, are locations of high crash concentration

In most countries 40 - 60% of the total number of crashes occurs at junctions. Consequently, special attention should be given in determining the type, the shape of junctions, as well as the number of junctions along a road axis and the efficient design of each one.

The main objective of junction design is to increase convenience, comfort and safety while at the same time enhancing the efficient movement of all road users (motor vehicles, buses, trucks, bicycles, and pedestrians), (Fitspatrick, 2005).

Junctions are intended to operate where vehicles often must share space with other vehicles and pedestrians. Negotiating a junction requires many simultaneous or closely spaced decisions, such as selection of the proper lane; manoeuvring to get into the proper position; need to decelerate, stop, or accelerate; and need to select a safe gap. The following basic areas should be reviewed in conjunction with these decisions to produce a satisfactory design: junction angle; coordination of the vertical profiles of the intersecting roads; coordination of horizontal and vertical alignment for junctions on curves; improvement of operation, safety, and capacity through channelization; and drainage requirements for safe operation. Not only must the horizontal layout be carefully thought out, but the coordination of the vertical and horizontal alignment should be given more emphasis. Poor integration of these two elements often results in a junction that is less safe and uncomfortable to use (Walker, 1993).

An important safety aim is to match the speed at which drivers negotiate the junction with the complexity of the decisions to be made. This can be done, for example, by only allowing simple merging manoeuvres on high speed roads or by ensuring that drivers reduce speed on the junction approach (e.g. by deflection of path through a roundabout). Sight lines should provide drivers with sufficient information to make safe decisions, but not tempt them to try to select short gaps in conflicting traffic flows.

More specifically, the main design principles for junctions include:

Minimization of traffic conflicts locations: A junction has a set of conflict points between vehicle paths, and a good design should aim at minimizing the severity of potential collisions at these points.
Sufficient sight distances: Appropriate sight distances, both while approaching the junction area and manoeuvring at the junction are of major importance for the safe operation of the junction. Important issues are the prompt perception and comprehension of the junction's layout and operation by drivers, particularly those who are not regular users of the junction, and the selection of appropriate path and travel speed; drivers can be assisted by improved

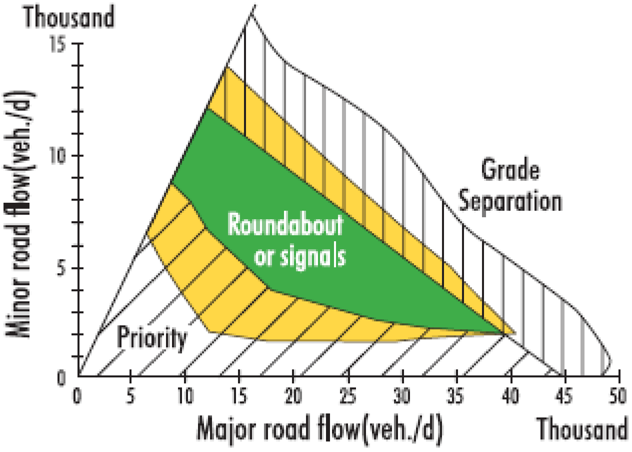
horizontal and vertical road marking and appropriate junction layout (Kuciemba & Cirillo,1992).
Appropriate longitudinal section and transverse gradients design: Ideally junctions should not have gradients over 3%, and never more than 6% in order to provide both improved comfort and sight distances; junctions should also preferably not be located at or near crest vertical curves (PIARC, 2003).
Management of turning movements, particularly those across the opposing traffic stream: this can be done by means of traffic islands and/or marked lanes, and by separate traffic signal phases.

The choice of a junction design depends upon several factors, whose relative importance varies between different locations. The most important ones are (PIARC, 2003):

- Traffic safety
- Road type and function
- Number of concurring legs
- Traffic volume and type
- Design and operating speed
- Priority setting
- Terrain
- Available room
- Adjacent land use
- Service to neighbouring population
- Network considerations (design consistency)
- Environmental concerns
- Cost

The type of junction has to be suited to the road type, the environment and capacity, in order to maintain good readability both of the road and of the junction, as well as a satisfactory level of safety. According to the above, for example, junctions or roundabouts should not be used on motorways, and signalized junctions need not to be used on rural roads, except in very special cases. The following Figure 1 shows guidelines for the selection of junction type according to traffic flows.

Figure 1: Type of junction based on traffic flows



Source: IHT, 1997

More specifically, the various types of junction present different advantages and limitations: Three- or four-arm non-signalized at grade junctions: These junctions may provide satisfactory road safety level when operating in low traffic volumes and speeds. Traffic islands and pavement marking, delimiting traffic directions and creating special lanes for left turning movements have a positive road safety effect (Neuman, 2003). When traffic volumes increase, it is necessary to establish traffic signals or consider modifications of the junction layout. In urban areas, changing a three- or four-arm level junction into a roundabout may lead to around a 30% crash reduction (Transport Department, 1995).

Roundabouts. Roundabouts have higher capacity than three- or four-arm non-signalized junctions; Roundabouts appear to have considerable safety advantages over other types of at-grade junction and are now being widely used in many countries (O'Cinneid & Troutbeck, 1998). However, their design needs to ensure adequate perception by drivers of the presence of motorized two-wheelers and bicycles.

Benefits of roundabouts

Converting junctions to roundabouts can improve safety and traffic flow. Roundabouts can contribute to road safety in the following ways (Elvik et al., 2009):

- Conflict points between the traffic streams are theoretically reduced
- Roads users entering the roundabout have to yield to road users already in the roundabout, thus they are forced to observe traffic at the roundabout more carefully
- All traffic comes from one direction
- Left turns are eliminated
- Speeds are reduced, as drivers have to drive around a traffic island located in the middle of a junction
- Roundabouts reduce the number of injury crashes depending on the number of arms and the previous form of traffic control. There appears to be a larger effect in junctions that used to have yield control than in junctions that used to be traffic controlled. Fatal crashes and serious injury crashes are reduced more than slight injury crashes (Elvik et al., 2009).

Source: Elvik et al., 2009

Signalized junctions. Signalized level junctions are the most common junction type in urban areas. Fatal crashes at signalized junctions are predominantly multi-vehicle (Antonucci, 2003). The majority of crashes on signalized junctions concern turning vehicle movement across opposing traffic or pedestrian's movement. Again care needs to be taken to avoid higher crash involvement, in relation to their traffic volumes, for motorized two-wheelers and bicycles.

Grade separated junctions (interchanges). These junctions present lower crash rates in general compared to at-grade junctions. It is noted that upgrading a three-arm non-signalized junction to a grade separated junction may result in a 50% crashes reduction, while the respective percentage for a four-arm junction may reach 75% (Transport Department, 1994-1). Research results have shown that reducing the number of lanes in the junction area, or designing weaving length of less than 1 kilometre, may have negative safety impact. Also, crash rates on the arms of the grade separated junctions are about higher compared to the sections outside junction. Additionally, crash severity rates on junction arms are higher compared to the related rates for interurban roads (not characterized as motorways) (Transport Department, 1992).

Effectiveness of junction treatment

Channelization at junctions is intended to:

- Segregate traffic flows from each other and reduce the area of conflict between different intersecting traffic streams
- Provide junction angles to give good visibility
- Define driving patterns and indicate which road has priority at a junction

It can be carried out by using traffic islands (physical channelization or road markings (painted channelization) and can include:

- Minor road channelization
- Left-turn lanes
- Passing lanes
- Full channelization

The majority of the various forms of channelization appear to have a more favourable effect on the number of collisions at crossroads than at T-junctions. There is a weak tendency that the more comprehensive the channelization methods are, the more favourable the effect on crashes.

Redesigning junctions includes:

- Change to the angle between roads
- Changes to the gradients of roads approaching the junction
- Other measures to improve sight conditions at junctions

Research results are very uncertain, however it can be deduced that an angle of less than 90 degrees gives the fewest injury crashes and the opposite appears to be the case for property damage only impacts. Moreover, a change in gradient on approaches to an junction from more than 3% to less than 3% appear to reduce the number of injury crashes, but increase the number of damage only crashes. The effect of increasing sight triangles at junctions was not found to be statistically significant in a number of studies.

Staggered junctions

Research results show that four-arm junctions have higher crash rates than three-arm junctions, because they have more conflict points between the streams of traffic. Staggered junctions aim at reducing the number of conflict points at junctions and can be constructed in two ways: left-right staggering and right-left staggering.

The effect of staggered junctions depends on the proportion of minor road traffic at the crossroads before staggering. When minor road traffic is low, no safety gains are obtained by dividing the crossroads into a staggered junction. When minor road traffic is heavy, the number of injury crashes may be significantly reduced.

Safe System choice of junctions varies with speed of traffic

For 120km/h roads, grade separated junctions are needed to ensure a *Safe System*. At 80 or 90km/h, well designed roundabouts should result in only a small risk of severe injury to car occupants but still pose higher risks to two-wheeled vehicle riders in collision with cars.

5.4 Roadside treatment

Crashes occurring on the roadside, as a result of vehicles running off the road, are an important proportion of the total number of crashes. Impact with roadside obstacles may cause significant injuries when such impacts occur. Roadside treatment aims at minimizing the probability of a, through appropriate roadside configuration (roadside design, land use etc.) and removal of aggressive obstacles. In case a vehicle runs off the road, the wider the roadside free zone is, the higher is the probability than the crash is avoided (PIARC 2003)

An important focus for treatment of roadsides is to create a forgiving environment. This means that if vehicles do leave the road their impact with any furniture that has to be located within the ideal clear zone should not result in serious injury. This can be achieved in two ways – placing a barrier in front of roadside object to deflect vehicles away from it, or using passive materials (i.e. that will breakaway on impact). Collapsible lighting columns were an early example of the latter approach; more recently passive designs for supports for large signs and for gantries are being trialled (Mesken et al., 2010).

Different restraint system designs utilize different levels of containment (e.g. standard – i.e. non-high containment - barriers will deflect cars but can be breached by heavier vehicles), and different working widths. Choice of type and siting of restraint systems at specific sites should take these characteristics into account. Restraint systems are very effective in reducing injury to car occupants but severe injuries do still occur. Growth in numbers of sports utility vehicles and light vans has also increased the proportion of vehicles not fully restrained by a standard barrier. Containment is provided by the longitudinal members of the restraint system. With steel and wire rope systems these members are carried by individual supports; impact between two-wheeler riders and these supports can result in more serious injuries than where a continuous face is provided by the restraint system.

Severity of injury in roadside impacts can be mitigated by improving design of both vehicles and infrastructure. It is particularly important that improvements are designed consistently to make sure the two systems work together to provide the safest outcome.

***Safe System* roadsides vary with speed of traffic**

For 120km/h roads, safety zones of at least 10 metres width are needed to ensure a *Safe System*. Roadside safety barriers can substantially reduce fatalities among belted car occupants but may still result in some severe injuries, particularly to riders of powered two-wheelers. Even at speeds of 70 or 80km/h, a safety zone of 3-4 metres width may be needed to achieve a *Safe System.*

5.5 Lighting

Sufficient lighting of roads and junctions can reduce crash risk at night. Around 35% of all reported crashes occur in the twilight or in the dark. The percentage is the same both inside and outside urban areas. The percentage of crashes in the dark is also higher for impacts involving pedestrians and crashes concerning vehicles running off the road (Elvik et al., 2009).

The objective of road lighting is to reduce the crash rate in the dark by making it easier to see the road, other drivers and the surroundings of the road. It is important to provide uniform lighting of the entire carriageway; therefore lighting should be also selected according to the reflective properties of the pavement. Lighting implementation is most important at junction areas, on roads around or approaching inhabited areas, and on roads with high traffic volumes and / or operating speeds.

Several studies have shown that the implementation of sufficient artificial lighting can reduce the number of crashes in the dark. Moreover, the effect of road lighting has a greater effect on impacts involving pedestrians in the dark than on other crashes. Additionally, the effect of road lighting does not vary significantly among different road environments (motorways, urban and rural areas). Improving existing lighting can also have a significant effect on reducing the number of road crashes. It should be noted, however, that the effect of road lighting may vary according to traffic and geometry characteristics of the road (road or junction type, traffic volume, speed limit etc.).

6 Management processes

Consideration of safety management principles should start when a road is initially planned, be carried through the design and construction phases, and continue to be applied through the life of the road. During its life a road may undergo many changes in the level of traffic flow it is serving, development of the area it passes through, and development of adjoining road networks. Regular appraisal is therefore needed of the road function and the appropriateness of its design to cater safely for this function.

Four groups of analysis tools have been developed to cover the different stages of the road life. These four tools are recommended as good practice for use on all road networks by the EU Infrastructure Directive, although only mandatory for the Trans European Road Network (European Commission, 2008).

6.1 Impact assessment

The impact on safety of transport projects or land use development should be evaluated at an early stage to avoid unintended adverse consequences, and to seek solutions for improving mobility and reducing congestion that are compatible with road safety. Before a decision is made to construct a new road or make a major change to the design or operation of an existing road, a safety impact assessment should be made (ETSC, 1997). This should assess impacts on the safety of surrounding roads or other transport networks, and requires network models that can show the potential casualty levels associated with different network layouts and traffic patterns.

Examples of Safety Impact Assessment tools

In UK, the SafeNET program includes modules for building networks of nodes and links and assigning expected crash frequencies to each link and node based on their design features and usage, enabling the total number of expected casualties resulting from different choices of overall network layout, detailed local design, and alternative traffic distributions to be assessed. Data are provided for both urban and rural networks (TRL).

In Netherlands, the Explorer program provides a tool by which traffic and crash data can be plotted onto a GIS base and risk of different road sections computed. Measures can be applied to network links and the effect on risk computed. The program also includes cost model by which the costs of measures and the value of the risk reduction can be compared. Measures include non-engineering changes such as increased enforcement (SWOV).

6.2 Safety audit of initial design and construction

Investigation of crashes occurring after a road has been built often indicate deficiencies in design that could have been eliminated at the design stage (AA & TMS, 1999). These deficiencies do not necessarily result from non-compliance with existing design guidelines, but more often reflect aspects of integration of design features that are not adequately covered in design manuals.

To counter this many countries have developed procedures for safety audit of designs for new road schemes. Typically, audits of major schemes might be made at three stages – preliminary design, detailed design, and pre-opening. For the largest schemes an earlier audit might be made as part of a feasibility study. For smaller schemes, the first two stages might be combined. Most countries adopting safety audit have produced detailed procedures and checklists for use by auditors, (IHT, 1990a; Transit New-Zealand, 1993; Danish Ministry of Transport,1997; Austroads, 1994; Austroads, 1992; NRA, 2000).
An extensive account of the practical issues associated with auditing is provided by Belcher (2008).

Safety audits in Britain

Since 1990 audits have been required for all Highway Agency roads and by 2000 most local highway authorities have audited major schemes and many minor schemes. Audit teams consist of two staff. For the third stage, it is common for the auditor to be accompanied by a police officer and a maintenance engineer. Visits are made during both day and night time. The client has to decide whether to act on the recommendations from the audit report, but must provide an exception report justifying his decision if no action is taken. In 2003 a fourth stage audit was added requiring a safety performance review after 3 and 5 years. Further revisions covered the qualifications for road safety auditors, discussion of the legal issues within road safety audit, and also provided advice to local highway authorities on appropriate resourcing for audit (IHT, 2008).

Safety audit in Australia and New Zealand

Safety audit has been applied for new State Highway projects in New Zealand since 1993 and subsequently by many local authorities. Audit was also adopted by Australian State highway authorities from the early 1990s and guidelines have been produced for use in both countries.

Improving the safety design of a project at the planning and design stages can save a significant number of lives and injuries over the life cycle of the project. Comparisons of audit costs with estimates of the potential crash savings that would result from proposed modifications at the audit stage. Wells (1999), Schelling (1995), Austroads (2002) and Transit New Zealand (1993) has shown that the benefit to cost ratio of audits average typically between 10:1 and 20:1 (ETSC, 1997).

A syllabus for European Road Safety Audit trainers has been produced by the European Commission (European Commission, 2007).

6.3 Regular casualty reduction remedial treatment

Road authorities are required to operate their roads safely. To do this it is necessary to monitor crash occurrence and to assess the scope for remedial treatment to reduce crash numbers and severity. This is most effectively done by maintaining a crash investigation and reduction team (IHT, 1990a). These teams are able to consider four types of treatment - treatment at individual problem sites (high-risk sites), route management over longer lengths of road, area treatment covering a network of roads, and mass action programmes which treat all sites at risk rather than just those where crashes have occurred in the past. Techniques for treating individual problem sites and for extending safety analysis to assess the quality of the whole network are discussed in section 7.

Countries with large numbers of high-risk crash sites are likely to focus initially on treatment of individual sites and corridor sections. Good analysis methods are required to ensure budgets are correctly targeted (see section 7.1) – an example of practice from a country with a recent programme is given in Szczuraszek (1999). Low-cost engineering solutions can produce high benefits at these sites (ETSC, 1996). As a crash reduction programme matures and crash density is reduced, the other types of treatment are likely to form a larger proportion of the programme, although individual site treatments will probably continue to be important if traffic conditions on the network change.

Example of crash analysis in France

In France the SURE approach has been developed to include driver perception of risk as a key part of assessing priorities for infrastructure improvement. Histories of high casualty rates can be used to identify sites where potential improvement is needed but similar sites will have different crash rates because drivers perceive their risk as different. Detailed analysis of crash reports are therefore needed to diagnose the causation factors. Site inspections are focussed on those road sections with high number of crashes and particular attention is paid to identifying the characteristics of sites which lead drivers to misjudge the real level of risk. Inspections aim to understand how the road functions in practice and apply remedial measures to aspects that result in incorrect function (SETRA).

Examples of risk analysis tools to support decisions on choice of treatments

In Australia, Risk Manager has been developed to assess hazards and rank potential treatments at a site. Hazard assessment involves modifying an estimate of general crash risk at a site, by local site conditions and design factors to give a relative risk estimate to the site and an estimate of casualty severity from the crash. Changes in the risks are estimated for potential treatments, again using general estimates of effectiveness modified by site conditions. The program allows treatments to be ranked by the effectiveness at the site, and provides an audit record of the assessment made (ARRB).

In the US, Safety Analyst is being developed to help identify and manage a system wide programme of site-specific improvements involving physical modifications to the highway system. It includes tools for network screening, diagnosis, countermeasure selection, economic appraisal, priority ranking and evaluation of implemented measures (FWHA).

To understand the effectiveness of crash reduction programmes it is important both to monitor the overall trend in crashes on the network, and also to record the effectiveness of the individual measures introduced. Knowledge that a particular measure has only had limited effectiveness at a particular type of site should lead to more efficient use of resources.

UK MOLASSES database of results of implementation of engineering schemes

Highway authorities in UK are encouraged to provide data to a central database on the effectiveness of low cost engineering measures implemented in their programmes. Information requested includes simple details of the site, type of measure implemented, costs, and crash numbers 3 years before and after the treatment. No attempt is made to describe site conditions in detail or to correct the difference in crash numbers for other factors varying between the time intervals. The results therefore are intended to give an indication of the average effects of treatments at sites which have generally been chosen because of their high risk; comparing data over time also gives some indication of whether treatment effects estimated on this basis are reducing. The response from authorities in providing such data is variable and thus the extent to which the results give a true picture across all sites treated is unclear).

Source: Gorell and Toothill, 2001

6.4 Audits of existing roads

Where historical crash data are sparse or assessment of the road safety risk can also be made through on-road inspections. These may focus on one specific aspect of road design or attempt to provide overall assessments of risk. Road safety inspection can be carried out periodically on an entire network, but also more frequently on road sections that have an above average number of crashes (SWOV, 2009 FS). Various assessment methods are currently used, and different countries use inspections for different purposes. Two attempts to develop more standardized processes are given in RIPORD-iSEREST, Report D5 and Castle et al., 2007).

Safety audit of existing roads in France

Machu (1996) describes a survey of roadside treatment over 2500 kilometres of road inspecting primarily the occurrence of aggressive roadside objects near to the road. In isolation however this information provides only a limited basis on which to assess the value of remedial action. A sample of urban roads was also inspected (Treve, 1997) and this work has been extended to assess ways of providing more forgiving urban roadside environments (Treve, 2003).

Audit of existing roads in New Zealand

Transfund New Zealand is developing the concept of safety audit of existing roads, looking for recurring patterns of deficiencies across the network, as a means of assessing how well road controlling authorities are performing.

Road Protection Score ratings in EuroRAP

The European Road Assessment Programme has developed a more comprehensive assessment of the extent to which road design protects road users from serious injury. This can be set alongside historical data on crash occurrence on these roads to indicate the scope for various treatments to improve protection. Similar programmes in Australia and North America are seeking to incorporate crash occurrence ratings within the overall assessment (Lynam et al., 2003).

See ERSO Safety Ratings web text

7 Casualty reduction programmes

Traditionally, casualty reduction programmes have been developed through analysis of historic crash data. This approach suffers from problems in statistical interpretation (7.1), particularly as casualty numbers decrease, and also requires several years of good quality casualty data before higher risk sites or road sections can be identified. Data on severe injury crashes is likely to be limited. As knowledge has increased on the effect of highway design on crash and injury risk, good estimates of relative risk in different parts of the road network can be made through assessing the quality of the road design and linking this to the speed of vehicles on the road and to driver behaviour based on perceived risk. Techniques for assessing network risk through audits of existing roads (such as the EuroRAP Road Protection Score) are being developed, with the results used alongside crash data, or replacing crash data when the latter are poor quality or do not exist, to guide road improvement programmes. These provide a clear link to *Safe System* (7.2) through identifying the combination of road environment and vehicle speed for which crashes are unlikely to result in severe injury. Historic crash data is always likely to play a part in highlighting specific problem sites, but more general assessment of network quality should enable preventative programmes so that the occurrence of unexpected problem sites is minimised.

7.1 Treating problem sites

Identifying sites for investigation

When authorities are seeking to improve road network safety, it is logical to consider for priority treatment those sections and sites which have high crash injury concentrations.

Higher than average crash concentrations can occur for two main reasons - high traffic flow at the site or specific factors other than flow resulting in hazardous conditions. It is important therefore not just to identify high crash concentrations but to identify those sites where crash concentrations are higher than would be expected for the level of traffic flow.

Examples of reasons for crash numbers above the expected number for a “safe” site of that type might be:an inappropriate choice of general road or junction standard (ref to initial design section re junction control)

- lack of provision of appropriate standard of facility for a manoeuvre that occurs more often than average at that site (e.g. separated turning lane)
- specific visibility problem (e.g. poorly located sign, vegetation obscuring sightline, crests or dips in the road)
- design of different aspects of the site not being “integrated” - safety audit
- deterioration of transient condition - e.g. skidding resistance

The RIPCORD project (RIPCORD-iSEREST, Report D6, 2008) defined nine steps in single site analysis and treatment:

- data collection (crashes, traffic road characteristics) – this needs to be unambiguously located on the network and each dataset should be interoperable with the others
- defining road sections – in simple terms by numbers or rates over 3-5 years, but ideally from a model based estimate. “Sliding windows” or “moving cursors” are often used to identify sites with high crash numbers. This approach defines sites in relation to location of crashes, but makes it difficult to establish a set of sampled sites which can be modelled.
- identifying and ranking sites for investigation – should be based on expected crash numbers due to local site conditions (ideally using Bayes method) and comparison with similar sites
- analysis of sites – using collision diagrams, crash characteristics, on-site inspection
- identification of proposed treatment to identify why crash happened
- pre-evaluation of proposed treatment – based on difference between best estimate of crash numbers before treatment and expected number after treatment
- ranking of projects within treatment programme – usually prioritised on basis of largest potential crash saving
- implementation
- post-evaluation – ideally using Bayes method but as a minimum controlling for long-term trends, taking account of any changes in traffic volumes and correcting for regression to mean effects.

Some aspects of the “ideal” methodology require extensive data and modelling to produce good estimates of expected crash numbers. Where possible the empirical Bayes method, which estimates expected crash numbers at a specific site from a weighted combination of observed crashes and the expected number of crashes from modelled similar sites, is recommended, but in some cases simpler methods may prove more practical (IHT, 2007) although less accurate.

Current practice falls short of ideal methodology (RIBCORD-iSEREST, 2008)- there is often no reference to populations of sites with most countries still apply sliding windows to count crash numbers, not all refer to “normal” levels of safety, virtually all use recorded crash numbers rather than an estimate of the expected local number of crashes based on actual site conditions, and not all make any allowance for crash severity.

Typical treatments and effectiveness

A wide range of treatments is available for single sites. Many will provide significant reductions in crash numbers or severity and high rates of return on investment due to the low cost of measures and the fact that if sites and treatments have been correctly selected, the measures closely target specific known crash types. A good summary of effectiveness of treatments is provided by Elvik et al. (2009).

Post evaluation should include an assessment of the whole safety programme – not just the individual treated sites.

Regression to the mean

Assessing sites for treatment can be confused if the effects of the random nature of crash occurrence are not properly taken into account. Many sites may be of a similar risk level, but in any relatively short period (e.g. 3 years which is often used for identification), crashes will occur at some of these sites but not others. The most important effect of this is that crash numbers at any single site will vary in a cyclic pattern over time. Ideally, to ensure the most appropriate sites are treated and that the effect of this treatment is correctly estimated, it is necessary to understand the long-term average crash rate at the site. Some sites may suffer crash numbers over a few years that are higher than this long-term average and thus appear strong candidates for treatment. After treatment, their crashes will probably fall, but part of this reduction would have occurred without the treatment and thus the effect of the treatment may be overestimated. This effect of crash numbers oscillating around a long-term mean is known as Regression to the Mean (RTM) -sometimes referred to as selection bias as it is likely that the sites where the crash numbers are temporarily above their long -term average are likely to be selected for treatment ahead of those with similar or possibly even higher long-term average numbers. Some advice on allowing for RTM is given in RIPCORD-iSEREST, Report D6 (2008) and (IHT, 2007).

Eliminating obvious problem sites

Having identified at one time all the sites that appear to have high crash numbers and treated them, it is sometimes unclear why new sites with high crash numbers are identified in a subsequent period. This can be due to changes in traffic flow or traffic behaviour – either as a direct result of site treatment or from other traffic or land use changes – for example, speed restrictions might encourage traffic to change to other routes, or improved road surfaces or bend re-alignment might encourage higher speeds on the treated route, making risk higher at other untreated sites along the route. The identification of new problem sites can also be due to worsening of transient effects, such as poor surface friction. But the apparent appearance of new sites may also reflect the effects of RTM, with sites which in the earlier period had crash numbers lower than their long-term average, now being associated with numbers reflecting their true risk. The concept of apparent crash migration between sites is also sometimes raised, but there is no clear explanation for this other than the processes mentioned above.

Thus although in the early days of developing road safety infrastructure strategy, programmes of individual site treatment are important where many high-risk sites (and their hazardous factors) can be identified, as the strategy matures it is important to look more broadly at network quality and the occurrence of risk within the network. Ways of doing this are described in section 7.2.

Countries are in very different stages of development of their highway safety programmes – for some (Greece, Italy, some central European countries) substantial single site programmes only started during the last decade (European Commission, 2003). Others have now moved on to network safety management (see section 7.2).

7.2 Network safety

Safety analysis of networks
A broader approach, now being followed by many countries (Finland, Sweden, UK, Norway, Denmark, Germany, Australasia) is network safety management (NSM) aimed at identifying more general improvements across the whole highway network (RIPCORD-iSEREST, Report D6,2008). In some countries this has virtually replaced single site treatment, in others it is used in parallel to a single site programme.

At a basic level, this involves identifying hazardous road sections, and the philosophy for identifying sites and treatments has similarities with the techniques for single site treatments. But the focus for network safety analysis is broader in that it involves preventative and prospective crash treatment, rather than only looking at past crash histories. It also involves longer road section lengths, a clearly defined population of roadway elements, and usually involves longer periods between assessments.

Typically network safety management includes (RIPCORD-iSEREST, Report D6 ,2008):

- Defining appropriate road sections (these can be short but are more usually up to 10 kilometres – the aim is for these sections to be homogenous in relation to the factors affecting crashes) and comparing these sections with the normal level of safety for similar sections (either using category analysis or more advanced prediction models
- Identifying hazardous sections using either the recorded number of crashes or the expected number taking account of local features within each section, based on Bayes method
- Allowing for crash severity by weighting numbers by cost of crashes of different severity
- Using crashes over 3 to 8 year periods

Instead of detailed individual site assessment, road inspections involve the whole road section, and consider not just the crash history of the section, but also look for deficiencies in design that might lead to future crashes. In Britain, where there are often several bends and local junctions along a typical road section, a route safety approach is often used (IHT, 2007), in which assessment over the whole road route between urban areas or between two major junctions includes both recorded crash history and the need for consistency of treatment of perceived risk at all sites along the route. In the US, Safety Analyst software has been produced to provide a comprehensive assessment system for network safety analysis (www.safetyanalyst.org).

Network crash models
The most accurate approaches to identifying sites or road sections for treatment and understanding their risk factors involve modelling of expected crash rates related to specific features at a site. One methodology developed for this is presented in the US Highway Safety Manual (AASHTO, 2010); this uses a base model for each type of road element to which crash modification factors are then applied which relate to the specific conditions at the site or road section being assessed. The models are largely based on evidence collected from US experience and are based more on motorised than non-motorised use. Other examples of network crash models include the Safety Performance function developed as part of RIPCORD (RIPCORD-iSEREST, Report, D2.1, 2008) and the iRAP assessment tool (iRAP, 2009) Tentative models of road user behaviour were also explored as part of RIPCORD (RIPCORD-iSEREST, Report D13, 2008).

Linking with *Safe System*
Although most network safety management programmes focus on defining practical highway improvement programmes within set budgets, the approach can be extended to demonstrate how a *Safe System* can be achieved. This requires that appropriate speed limits and design standards are set for each part of the road network, and the whole network is assessed to determine where it falls short of these standards. Action is then required either to modify the speed limit or to bring the road design up to the acceptable standard across the whole network. One example of this approach to assessment is provided by EuroRAP where road sections are rated according to their current design and operating conditions, and potential crash saving estimated if the road is improved to achieve a specific (*Safe System*) rating. Such improvement can often be justified in economic terms on roads where flows are high, but this is more difficult for low flow roads. Innovative cost-effective treatments are required for these roads, such as the 2+1 Roads with a central barrier being applied extensively in Sweden (SRA, 2006) and are achieving good results (Lie, 2010).

In the UK, increasing recognition of road safety as a public health and work–related problem has led to road risks being considered in a similar way to general health and safety regulation (IHT, 2007). Such regulation typically categorises upper and lower risk levels as unacceptable or broadly acceptable, with a middle risk band within which risk should be made “as low as reasonably practical” (ALARP). The most obvious application of this approach is to the safety of workers on the road, and is also be applied to some road design standards.

Risk assessment in design

Traditionally design standards for individual road elements have been defined in terms of various categories of road type, traffic flow, etc with designers selecting from a set of criteria appropriate to the site being considered. The philosophies behind *Vision Zero* and *Sustainable Safety* require designers to consider more deeply how to limit the injury risk to road users taking all site conditions into account. The UK approach to this to date can be seen in the Highways Agency standard for roadside safety fences in UK (Highways Agency), where designers are required to calculate the risk associated with different design choices and ensure they choose an option where risk falls within defined limits. These limits are set either at a broadly acceptable “safe” level or “as low as reasonable possible” taking account of the cost of the measures. The need for a safety fence can be avoided by clearing the roadside of obstacles or utilizing passively safe infrastructure.

Network Management and Sustainable Safety

There is a trend at regional level in the Netherlands to concentrate traffic no longer on motorways, but to divert some of it to the secondary road network. There is concern that this will lead to more road crashes unless additional safety measures are taken on these roads. SWOV has proposed a network test to check whether roads are to an appropriate standard for the function they are required to meet and a *Sustainable Safety* Indicator to test whether these roads meet appropriate safety standards.

Source: SWOV 2010 Fact sheet on Network Safety and Sustainable Safety.(SWOV,2010 FS).

8 Managing safe road operation

8.1 Speed limits and enforcement

Safe road systems can only be achieved by an appropriate combination of vehicle speed and road design. Ensuring speed limits are set at levels consistent with the function and design of the road is thus very important. The role of speed in road safety is now well understood (Elvik, 2009; ERSO Speeding text). Enforcement strategies can be deployed effectively where drivers flout the speed regulations (ERSO Speed Enforcement text). Recent experience has shown average speed cameras to provide a particularly useful tool. At the same time, ensuring road design incorporates “self explaining” features (section 2.3) can help encourage most drivers to keep their speed within the limits providing these are consistent with those features.

8.2 Role of road and pavement maintenance

The skid resistance of a road pavement is an important road safety factor, especially when the road surface is wet. A concentration of crashes on a wet surface can therefore be an indicator of friction deficiency. The risk of crashes is elevated even more where the problem is at a location where the friction requirement is high (e.g. approach to an junction, horizontal curve, downhill slope) or where the problem is isolated (e.g. road surface contamination).

Drivers may have difficulty in recognizing sites with skid resistance problems and as such, they may not reduce their speed at those locations, as would be necessary to maintain their risk at a level they consider acceptable. Several studies have shown that there is a significant correlation between crash risk due to skidding and the pavement's skid resistance. The coefficient of friction ranges from nearly 0 under icy conditions up to above 1.0 under the best surface conditions (PIARC, 2003). Crash risk due to vehicle skidding on pavements with friction coefficient (SFC) less than 0.45, is 20 times higher than on pavement surface with a SFC higher than 0.60. Moreover, if the SFC of a road is less than 0.30, crash risk is 300 times higher (Transport Department, 1994-2).

Crash risk is higher when the skid resistance is low.

Crashes that are related to friction deficiencies occur mostly under wet surface conditions because the available friction is then reduced (PIARC, 2003). These concentrations of wet surface crashes are worst at road locations having both a poor skid resistance and a high friction demand. (Viner et al., 2005) conclude that amongst the most potentially dangerous driving conditions are those caused by low friction due to heavy rainfall combined with poor road geometry, or those where there is a sudden change in friction, perhaps due to contamination, localized deterioration of the surface or first snowfall.

Two main characteristics of pavement surface affect skid resistance: microtexture and macrotexture. The role of each in providing sufficient friction varies depending on the speed (Noyce, 2005; Roe et al., 1998). However, the most important factor affecting skid resistance is pavement macrotexture, which is the feature that increases skid resistance at high travel speed. Crash risk increases when texture depth drops below 0.7 millimetres (TRL, 1991; Gothie, 1996).

Evenness is a measure of the regularity of a road surface. All types of road surfaces (rigid, flexible, gravel, etc.) deteriorate at a rate which varies according to the combined action of several factors, such as the axial load of vehicles, the traffic volumes, the weather conditions, the quality of materials and the construction techniques (PIARC, 2003). These deteriorations have an impact on the road surface roughness by causing cracking, deformation or disintegration. Water concentration on these deteriorations increases the risk of vehicles skidding.

When the evenness of a whole road section has sharply deteriorated, users tend to reduce their speed in order to maintain their comfort at an acceptable level, thus minimizing potential safety impacts. Pavement roughness can however be more detrimental to safety when problems are localized, unexpected and significant. Such situations can generate dangerous avoidance manoeuvres, losses of control or mechanical breakdowns of vehicles, thereby increasing the risk of crashes. Reductions in skid resistance caused by vertical oscillations of vehicles on uneven road surfaces can prove problematic, especially for heavy vehicles and when the problems are isolated (PIARC, 2003).

Pavement roughness and safety

- The safety impact of pavement roughness varies according to the type of crash considered (Al-Masaeid, 1997):
- The single-vehicle crash rate decreases as the pavement roughness increases, due to reduced speeds;
- The multi-vehicle crash rate increases, due to lateral shifts and speed differentials between road users.
- However, one should also be aware that an improvement in the evenness quality associated with resurfacing may result in speed increases, thereby having a slightly negative safety effect.

8.3 Safety of road workers

Most studies show an increased crash rate at road works, with most crashes being vehicle to vehicle rear end impacts. Good signing (e.g. VMS) is important in encouraging drivers to negotiate the roadwork are safely. More critical is the safety of those within work zones. While high-visibility clothing and, where practical, the use of vehicle impact attenuators can help, the acceptable risk levels for road workers are being considered more comprehensively with risk values being aligned to Health and Safety guidelines by some authorities. Ensuring drivers adopt lower vehicle speeds through the work zones is an important factor but the limit must reflect safety needs. For example in the Netherlands limits are often only reduced to 90km/h, although 70km/h is used where driving lanes are narrow or workers are close to the carriageway without protective barriers. Feedback to drivers on speeds appears to result in speed reductions. In UK, speed limits at roadworks are often enforced by speed cameras (particularly cameras checking average speeds over the length of the roadworks).

9 Roads need to cater safely for all users

Road design should reduce the probability of crashes in advance, by means of the infrastructural design, and where crashes do occur, the process which determines the severity of these crashes should be influenced such that the possibility of serious injury is virtually eliminated. Thus, a sustainable, safe traffic system has (PROMISING, 1998).

- A structure that is adapted to the limitations of human capacity through proper design, and in which streets and roads have a neatly appointed function, as a result of which improper use is prevented

- Vehicles fitted with ways to simplify the driver’s tasks and constructed to protect the vulnerable human being as effectively as possible; and
- A road-user who is adequately educated, informed and, where necessary, guided and restricted.

The concept can be translated into some, more practically oriented, safety principles:

- Prevent unintended use, i.e. use that is inappropriate to the function of that road
- Prevent large discrepancies in speed, direction and mass at moderate and high speeds, i.e. reduce the possibility of serious conflicts in advance
- Prevent uncertainty amongst road-users, i.e. enhance the predictability of the course of the road or street and people's Behaviour on the road.

Standards and criteria for sight distance, horizontal and vertical alignment, and associated traffic control devices are based on the following driver performance characteristics: detection and recognition time, perception-reaction time, decision and response time, time to perform brake and accelerator movements, manoeuvre time, and (if applicable) time to shift gears. However, these values have typically been based on driving performance (or surrogate driving measures) of the entire driving population. The models underlying these design standards and criteria therefore have not, as a rule, included variations to account for the special characteristics or performance deficits consistently demonstrated in research on vulnerable road users. On that purpose, specific guidelines to address the needs of for these special user categories are often proposed (TRB, 2004)

9.1 Pedestrians

Pedestrians form the second largest group of road casualties (after car occupants). They account for about 20% of the road fatalities in the European Union (EU27). The over-55 and under-12 age groups are those with the highest risk of becoming pedestrian casualties. In most countries, crashes involving pedestrians (apart from those resulting in fatal injuries) tend to be underreported (PROMISING, 1998).

Design principles and measures for improving pedestrian safety include (PROMISING, 1998):

- Adequate capacity of pedestrian walking facilities in relation to pedestrian flows
- Smooth and non-slippery surfacing for comfortable walking
- Avoidance of steep gradients that may not be usable by elderly or disabled pedestrians
- Elimination of all obstacles likely to obstruct pedestrian routes
- Specific direction signing for pedestrians, particularly on the links of the network segregated from motor traffic
- Reduction of vehicle speed on links of the network with mixed traffic (residential, commercial or historical streets)
- Adequate lighting
- Clearance of snow, ice or dead leaves from pedestrian walking facilities as soon as needed
- Repair of holes and otherwise damaged surfacing as soon as needed

- Reduced risk for pedestrians when crossing in the right place (design must ensure that vehicle users behave as expected)
- Local continuity of walking route and reduced physical effort
- Reduced waiting time and long enough gaps in traffic for safe crossing (traffic light management); conflict-free crossing at traffic lights
- Adequate mutual visibility of pedestrians and drivers on the approaches to the crossing
- Possibility of crossing safely all along links with particular specifications (commercial streets, leisure or residential areas): reduced width of carriageway to cross or reduced speed of vehicles
- Keep the crossing facilities in good repair (especially markings)
- Keep the approaches to the crossing clear of obstacles

A fuller discussion of the issues associated with pedestrian safety is given in ERSO Pedestrians and Cyclists web text.

9.2 Cyclists

Cyclists comprised around 6% of total EU (27) road traffic deaths in 2010 but a higher share of total deaths (though often lower injury risks) in countries where cycle use is high e.g. the Netherlands. The number of cyclists killed per cycled kilometre is very much influenced by the total number of cycled kilometres. The crash risk based on the amount of cycling is lowest in Denmark and the Netherlands. The risk is particularly high in France and Great-Britain where the amount of cycling is low. It has been proven that the risk decreases as exposure increases. An increase in cycling is not automatically linked with a linear increase in road casualties (PROMISING, 1998).

When facilities for cyclists are being designed, five criteria are important if their needs are to be met (PROMISING, 1998).

Safety: improvement of the safety of cyclists on the road is therefore a precondition for promotion of cycling
Coherence: continuity, consistency of quality, recognizability and completeness
Directness: mean travel time, detours and delays
Comfort: smoothness of road surface, curves, gradients, number of stops between starting point and destination, complexity of rider’s task
Attractiveness: visual quality of the road, surveyability, variety of environment and social safety.

Moreover, design principles and measures for improving cyclist's safety include (PROMISING, 1998):

Grade-separated crossings for crossing main roads (urban motorways, main arterials etc)

- Frequent crossing possibilities along main roads, in order to prevent the barrier effect for cyclists
- Wide cycle tracks and wide pavements along main roads, affording cyclists good accessibility, safety and security
- Junctions provided with crossings for cyclists
- Minimization of waiting time for cyclists at crossings (cyclists should be provided with the same rights as motor traffic)
- In urban areas, cycling (as well as walking) should receive first priority, except on some roads with a traffic flow function for cars only.

The safety of cycling facilities is often reduced drastically by a lack of proper solutions at crossings. Cyclists' safety at crossings can be promoted by right-of-way regulations, speed reduction measures and improved visibility. Examples of speed reduction measures are raised bicycle crossings, humps, refuges in crossings, and mini roundabouts. Additionally, important features for improvement of visibility are: truncated cycle tracks, advanced stop lines at signalized junctions, and parking regulations.

To ensure first priority for cyclists (and pedestrians), technical measures are needed, supported by rules. Possibilities are (PROMISING, 1998):

- Advanced stopping lines at crossings with traffic lights, to enable cyclists to wait in front of motor traffic and to continue first
- Leading phase for cyclists and pedestrians
- Traffic lights that provide a green phase to cyclists and pedestrians twice during each cycle
- Detectors that provide cyclists and pedestrians with green light as soon as they arrive at a crossing
- Providing cyclists with the right to turn right when motor traffic has to wait at a red light.

A fuller discussion of the issues associated with pedestrian safety is given in ERSO Pedestrians and Cyclists web text).

9.3 Motorized two-wheelers

Motorcycle and moped fatalities EU 27 represented 17% of all traffic fatalities in 2010. For both mopeds and motorcycles, the rate of fatalities per 10^5 vehicles is much higher for younger riders than for older riders.

Road design should take into account the special needs of riders of mopeds/motorcycles in terms of both the design and maintenance of the road. These riders are much more vulnerable to imperfections of the road surface than car drivers, and special requirements have to be recognized for road markings, road surface repairs, longitudinal grooves, drainage etc.

Although many improvements to the design of roads and traffic control measures will have the same positive effect on the safety of riders of mopeds/motorcycles as on that of other road-users, this is not the case with all speed-reducing measures. These measures may pose special problems for mopeds/motorcycles and should be tested to prevent such problems. At the same time, speed reduction measures warrant review to better guarantee that riders of motorized two wheelers keep to the limit. Greater use of two-wheelers may contribute to the solution of congestion problems but these and safety outcomes need to be carefully balanced. Experience in Malaysia and elsewhere indicates that separated lanes for motorcycles/mopeds as distinct from other motor vehicle traffic is a demonstrably effective strategy. On the other hand, it is also important to separate motorcycles and mopeds from cyclists and pedestrians.

A fuller discussion of the issues associated with pedestrian safety is given in ERSO Powered two wheeler web text.

9.4 Young drivers

It can be seen that in almost all European countries road crashes are the major cause of death among young people. Per 100,000 inhabitants, 3 times as many people aged between 18 and 20 and twice as many aged between 21 and 24 die in cars as people aged between 25 and 65. Young riders and drivers are more often to blame for errors that cause crashes than older riders and drivers (PROMISING, 1998).

Several characteristics of young drivers that are related to traffic engineering countermeasures can be identified (FHWA, 2001):

Visual Search: Young drivers tend to have more vehicle-centered looking than up-road looking.
Automaticity: Young drivers have not acquired the automaticity of certain driving tasks that is gained with experience and that allows fluid switching between driving tasks under stressful conditions.
Hazard Detection: Young drivers, in general, detect traffic hazards less reliably and more slowly than experienced drivers.
Perception of Risk: Young drivers tend to perceive less risk associated with traffic hazards.
Attention Allocation: Young drivers are more easily distracted by non-driving related events, such as conversations that occur between passengers in the car and controlling the vehicle audio system.
Self-Assessment: Young drivers tend to overestimate their ability to control a vehicle under emergency conditions.
Comprehension of Traffic Control Devices: Young drivers may not understand the meaning of traffic control devices as much as experienced drivers, and seem to use the devices less than is ideal.
Vehicle Control: Young drivers are less skilled at making emergency manoeuvres and are vulnerable to overcorrection errors that lead to loss of control.
Anticipation: Young drivers, in general, show less ability to anticipate emerging traffic hazards.

Specific roadway design features known to be problematic for young drivers include the negotiation of horizontal curves and junctions. Several studies analyze young driver problems in detail to develop improved design and operational guidelines and countermeasures. A fuller discussion of the issues associated with pedestrian safety is given in ERSO Novice Drivers web text.

9.5 Older Drivers

In many countries the fatality rate for older people on the roads is about 1.5 times the average, largely due to their physical vulnerability. Older drivers do, however, have lower exposure to risk.

Diminished visual performance (reduced acuity and contrast sensitivity), physical capability (reduced strength to perform control movements and sensitivity to lateral force), cognitive performance (attentional deficits and declines in choice reaction time in responses to unpredictable stimuli), and perceptual abilities (reduced accuracy of processing speed-distance information as required for gap judgments) combine to make the task of negotiating the road design elements more difficult and less forgiving for older drivers (TRB, 2004).

Research results (Benekohal, 1992) show that the following activities become more difficult for drivers as they grow older:

- Reading street signs in town
- Driving across an junction
- Finding the beginning of a left-turn lane at an junction
- Making a left turn at an junction
- Following pavement markings
- Responding to traffic signals
- Manoeuvering at weaving areas (e.g. at-grade junctions)

Benekohal (1992) also found that the following road features become more important to drivers as they age:

- Lighting at junctions
- Pavement markings at junctions
- Number of left-turn lanes at an junction
- Width of travel lanes
- Concrete lane guides (raised channelization) for turns at junctions
- Size of traffic signals at junctions

Recommendations to enhance the performance of diminished-capacity drivers as they approach and travel through junctions, may include: intersecting angle (skew); lane width for turning operations; channelization; junction sight distance; left-turn lane geometry, signing, and delineation; treatments/delineation of curbs, medians, and obstacles; curb radius; traffic control; signage; lane assignment on junction approach; traffic signal performance issues; lighting installations; and pedestrian control devices (NCHRP, 2005).

A fuller discussion of the issues associated with pedestrian safety is given in ERSO Older Drivers text web text.

10 eSafety and infrastructure

10.1 Intelligent infrastructure

Intelligent infrastructure includes the road network, its sensors, traffic information centres, vehicle, and the communication networks linking these components. Three types of communication can be used; the list below gives examples of systems (Bell, 2006).

Vehicle to vehicle or within vehicle
Autonomous emergency braking, Road condition warning
Collision avoidance systems, Emergency approaching vehicles
Vehicle to road
Curve speed warning, traffic signal violation warning
Lane or road departure warning, right turn and give way junction assistance
Vehicle to vehicle and vehicle to road
Intersection collision warning, rail crossing collision warning, road works warning - near
Motorway merge assistance, pre-crash sensing

Initial ideas on intelligent systems focussed on producing “Automated Highways”; more recently systems have been viewed more as “Co-operative vehicle-highway systems”. Most currently proposed systems aim at guidance, informing, and warning drivers rather than taking over control of the vehicle.

10.2 Vehicle Highway Systems

Automated highways were seen as a means of increasing vehicle flow by reducing vehicle spacings beyond that within which humans can be expected to react safely. This would be achieved by utilising automatic vehicle based systems for close following and cruise control. Failure of the automatic systems could still lead to injury crashes; “brakes full on” failures are likely to be more dangerous than “no brakes failure” (Hitchcock, 1995). The aim is to move vehicles in close following platoons, with the hope that collisions would occur below the relative speed thresholds at which deaths are likely to occur. Such a system was demonstrated in 1997 in USA, involving both platooning and free agent operation. The feasibility of platooning was demonstrated using vehicles following buried magnets; free agent vehicles used vision and radar communication.

Co-operative Vehicle Highway Systems programmes developed in Europe over the last decade (mainly from initiatives by vehicle manufacturers and road operators) include
CIVIS - designing and testing core technologies for co-operative systems
SAFESPOT – co-operative systems for processing highly critical factors (usually warning or information systems) ; they combine data from vehicle and roadside sensors to give a Local Dynamic Map of the vehicle surroundings, aimed at extending the time difference between detecting potential danger and expected time of impact if no action is taken.
COOPERS - this is the road operators view and includes a 3000 kilometre motorway demonstration Programmes outside Europe include PATH (US) and SMARTWAY (Japan).

10.3 Road-Vehicle Communication

Traditional systems such as inductive loops buried beneath roads are being extended and replaced by microwave radar, infrared sensors, ultrasonic detectors and acoustic devices. An Intelligent Infrastructure will look very much like today’s infrastructure. But the road will be very different in how it operates and what it does for the people who use it.

Although vehicle mounted systems can use radar or image processing, short range wireless communication is needed for systems transmitting to or from the highway (Bell, 2006); as yet there are no standards for dedicated short range communication systems. Micro wave communication system that can provide fast vehicle roadside link enabling real-time transmission of data from on-board sensors would enable sensing information in real time about vehicles and surroundings.

The key to meaningful telematics is ubiquitous positioning and communication (knowing the position, speed and heading of each vehicle). Vehicle based safety functions (collision avoidance, lane change warning) need highly accurate data on position/ speed/headway. Others functions (e.g. traffic light control) require less accurate but need to be kept up-to-date. Past GPS has not been sufficiently accurate to support these systems, but Galileo should offer a significant increase in performance and integrity (McDonald, 2006).

The use of miniature, low cost, and maintenance free sensors within the road surface using wireless communication with each other and with the remaining infrastructure is being investigated (Lagiola & Oonk, 2009); the main technology challenges relate to power harvesting, data-interpretation and efficient installation. A major future challenge is to reduce the size of sensors to so-called “SMARTDUST” (Arief et al., 2007).

In the meantime, some interactive capabilities can be achieved through traditional methods such as beacons, sign recognition, speed detectors, lane/edge markings, and variable message signs. Speed limits could also be map based in navigation systems. Traffic sign recognition (which could enable speed limit and no overtaking warnings) is likely to use vision based detection and recognition software. “Intelligent” road studs can also offer some driver support and “investigation of driver behaviour with illuminated studs compared with standard retro-reflective studs showed that drivers demonstrated more consistent braking on the approach to bends and improve control within bends when the actively illuminated studs were present.”(TRL Vehicle Safety).

It is important to see intelligent infrastructure as a system, even in its early days of implementation. For example, lane departure and lane assist systems are likely to become common, and will not work unless the vehicle can navigate locally. Currently lane marking provides the basis for this local navigation, and of these markings are not readable in an adequate way, these car based systems will not be effective.

Autonomous driving in structured environments (e.g. within marked lanes) can use visual lane recognition; driving within unstructured environments (e.g. parking zones) might be simulated using a detailed model or map of the road or driving area.

10.4 Implementation within road network

Fully automated highway systems are only likely on high quality limited access roads. Most road networks are not yet fitted with wireless infrastructure, although there have been short trials in several European countries. The eventual aim for co-operative vehicle highway systems would be for the vehicles to be “always connected” to the infrastructure.

Co-operation could exist at 3 levels (McDonald, 2006)

- Vehicle receives data from highway - vehicle must locate itself and then highway data can allow the driver to anticipate future conditions (road curvature, congestion, speed limit).
- Highway receives data from vehicle – this can enable the highway operator to implement control strategies to reduce risk.
- Fully co-operative vehicle-highway information flow – this could, for example, allow merge control at access points, but may not be likely in the foreseeable future.

Some systems would need very detailed local highway information. For example, lane departure warning and lane keeping support systems would need to recognise lane mark type (continuous, discontinuous, merge) and tell the difference between allowed and forbidden movements (e.g. crossing a continuous line). Intersection safety support systems might simply warn of the presence of intersections, warn of the presence of vehicles in side roads at those junctions, or help drivers to make decisions on turning movements. In the latter case, accurate and reliable data would be needed not only on the status of other vehicles but also of the status of control devices (e.g. traffic signals) at the intersection.

Public-private partnerships may be most effective way to deploy co-operative systems, involving both the relevant traffic authorities and vehicle manufacturers. Problems to be overcome include the need to resolve privacy, data ownership and access and liability issues, and also how much risk should be taken by the private sector. Interoperability (nationally and across Europe) is a further important consideration.

10.5 Effectiveness

Evaluations of interactive signing systems and dynamic speed limits, as used on managed motorways, have shown safety benefits McDonald et al., 2000). Dynamic traffic management systems (VMS) reduce all injury crashes by 5-20% and fatal crashes by 10-25%, but the impact depends on the quality of the system (ref. www.esafety-effects-database.org). Provision of information warning drivers of incidents ahead and estimated time of incident appears to help drivers make more rational decisions.

For more complex co-operative systems, the need for accuracy, reliability and acceptability is paramount. For systems involving, for example, speed limit, stop sign, or turn restriction information, it is essential to have precise map-based data.

Systems which involve taking over some degree of control of the vehicle must have an adequate fail safe option. The focus for this should be to prevent fatal and severe crashes, so some minor impacts might be accepted. Possible side effects of co-operative systems could be diminished attention level, information overload, incorrect interpretation of information, overestimating system capability, and risk compensation or behaviour adaptation. There could also be negative effects for non-users of the system. Semi-automated vehicles could be less safe than human drivers if human intervention (from a relaxed state) required as fail-safe. However the potential safety benefits that might be achievable for a fully automated system are likely to encourage a continued drive towards automation.

Acceptability issues might be less severe if systems bring added benefits such as an increased ability to drive for longer by an ageing population through various driver assistance systems and intersection collision warnings. One report (ref Foresight Overview)has suggested “Intelligent vehicles could see the end of age restrictions on the use of private vehicles, bringing enormous benefits to an ageing population.”

For the present, evidence of the effectiveness of co-operative systems remains limited. For most systems, such as lane departure warning, extended environmental information, and local danger warning and collision warning, estimates of effectiveness are based on simulator studies, small field behavioural trials and analysis of crash causation factors, and provide little hard evidence (www.esafety-effects-database.org).

See ERSO eSafety web text.

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ERSO Road Safety Management text.

ERSO eSafety text.

ERSO Vehicle Safety text.

ERSO Older Drivers text.

ERSO Pedestrians and Cyclists text.

ERSO Powered two wheeler text.

ERSO Speeding text.

ERSO Speed Enforcement text.

ERSO Novice Drivers text.

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