Roads

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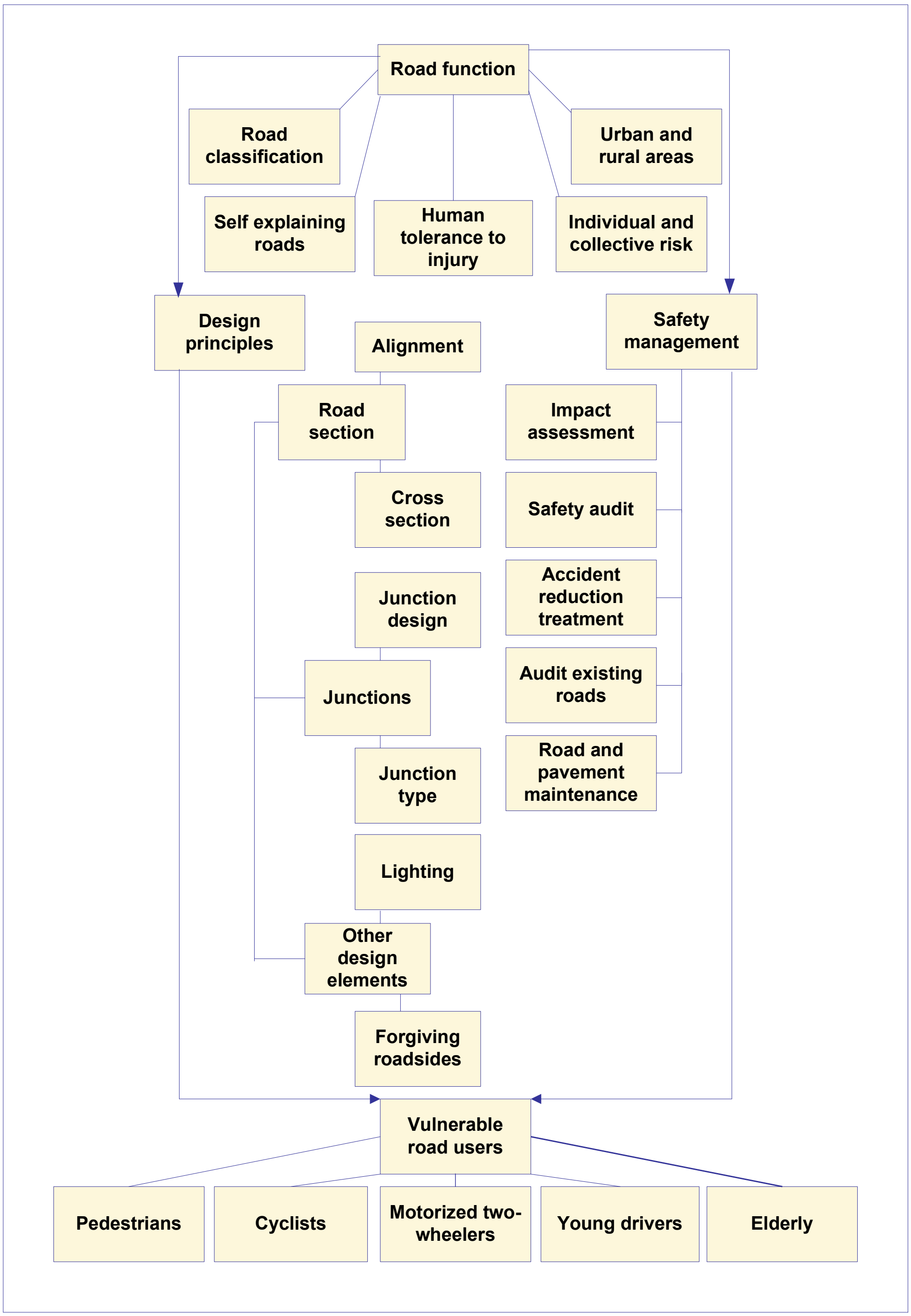
1. Roads

Diagram & Summary



Many of the basic principles for good road design were developed up to 40 years ago, and are still valid today. Although further refinements have been explored since then, there still remains uncertainty about relationships associated with design details and recent engineering innovations. A good commentary on the issues still associated with several engineering safety topics is provided at www.roadsafetyresearch.com.

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. By adopting a consistent and clearly differentiated design for each function group, driver's subjective assessment of risk can be better actual risk. This in turn encourages road user behavior consistent with the safety standard of the road. The same general functional management principles should be applied in both urban and rural networks. 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.

Getting initial safety design principles right

Accident rates 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 accidents likely to occur and to mitigate injury severity, particularly on higher speed roads.

Managing safety of roads through their whole life

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 accident investigation and on-road inspection to enable cost effective remedial programmes to be developed; many tools exist to support these activities. The skid resistance of a road surface is an important road safety factor; both micro-texture and macro-texture of the surface play a part.

Roads need to cater safely for all users

The design of roads should be adapted to the limitations of human capacity. 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.

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 safety management principles in urban areas can produce overall accident reductions of at least 15% [17]. There are also good examples of integrating safety management with other urban planning objectives [65]. Similarly it is well established that most serious injury accidents on rural roads are associated with a small number of accident types which can be addressed by different aspects of engineering design [66]. These accident types occur in different patterns on roads with different designs and speed limits [53]. 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 [102].

2.1.1 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.

2.1.2 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.

2.1.3 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 accident rate (both per km and per vehicle km) on the different road types [53], and thus national accident 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 behavior and road design will be optimized where the road design gives a clear message to road user of the function of the road, and the hazards that are likely to be encountered.

High proportion of traffic on motorways in the Netherlands influences fatality rates
An intensive period of motorway building during 1970s and 1980s in the Netherlands has resulted in the 40% of the national total of vehicle kms 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)

Risk on any specific road can be defined in terms of risk to each individual driver using the road (accidents per vehicle km) or 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 accidents 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 accident reduction is still likely to be worthwhile on those low flow roads where individual risk is significantly higher than average for these roads.

Current accident databases reflect the road classifications used by the accident 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.

2.1.4 Self explaining roads

The concept of self-explaining roads on which the driver is encouraged to naturally adopt behavior consistent with design and function originated in the Netherlands [84] [55]. 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 behavior.

Such an approach 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.

These concepts are being developed further in current European projects [76][74] to understand which design features modify driver behavior to accord with the road function, and result in speed choice consistent with the safe speed for that design and function.

2.2 Urban and rural networks

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.

2.2.1 Urban

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

Accidents in residential areas are characterized by larger proportions of accidents involving children and the elderly and accident locations scattered widely rather than concentrated at black spots [64]. The majority of the accidents 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 accident risk, with absolute number of accidents being higher in older layouts

Area-wide measures are therefore necessary for the design and implementation of countermeasures. Measures must not only address accident 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.

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 accident 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 safety schemes
- Monitor progress towards safety objectives

Four steps in defining functions and objectives are

- Identify current road hierarchy
- Appraise extent and characteristics of accidents 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 [65]. 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 [23].

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

2.2.2 Rural

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 accident rates per vehicle km can be up to six times higher on 2 lane rural roads than on motorways, and decrease as traffic flows increase [52]. The density of severe (fatal and serious injury) accidents per km 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 accidents on major interurban roads occur due to single vehicles leaving the road, impacts at junctions, head-on impacts with opposing vehicles or impacts involving vulnerable road users [66][51].
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 [53].

The European Union has published guidelines for the design and management of the Trans European Network, and is currently consulting on an infrastructure Directive. Several European research projects [77] have developed advice on design standards for interurban rural roads.

2.3 Designing to keep injury severity low

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 (ref vehicle safety and speed chapters). Similar criteria could be used to align the protective design of a road to counter impacts between cars and roadside objects, or to limit the possibility of higher speed vehicle to vehicle impacts through median and junction design [85][52]. 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.

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 these are being used in Sweden to indicate appropriate speed limits for roads with different ratings.

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 Safe 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 behavior 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.

Source: Wegman et al (2005), Wegman & Aarts, 2005 (page 14; translated from Dutch)

Measures to minimize injury severity include creation of clear zones alongside roads (see section 2), use of passively safe materials or shielding of objects where impact would involve higher energy levels than those leading to tolerable injury levels [22].

2.4 Individual and collective risk

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 [70] 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 accident costs can be used to identify roads on which potential improvements would be worthwhile is given in [8]. The EuroRAP programme provides a basis by which roads having high numbers of fatal and serious accidents compared with expected numbers for that road type can be identified within national rural road networks.

3. Getting initial safety design principles right

Road safety analysis has contributed to the international experience on identifying relationships among various road design elements and accident 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.

3.1 Road sections

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.

3.1.1 Horizontal 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 (Figure 1). 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.

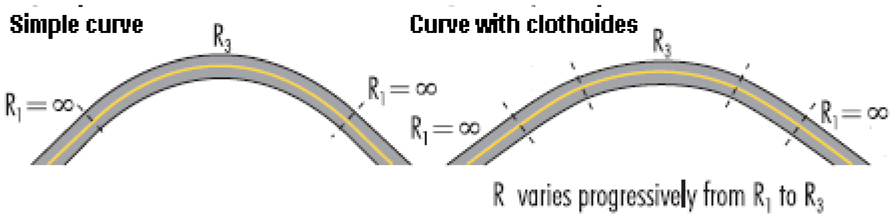


Figure 1 Sequence of horizontal alignment components (PIARC: 2003)

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

- The accident rate in curves is 1.5 to 4 times higher than in tangents (i.e. straight sections) [107]
- The severity of accidents in curves is high [30] 25 to 30% of all fatal accidents occur in curves [50]
- Secondary rural roads, which are built following lower design standards (including more and sharper horizontal curves) have on average a higher proportion of accidents in curves [80]
- Approximately 60% of all accidents to occur in horizontal curves are single-vehicle off-road accidents [50]
- The proportion of accidents on wet surfaces is high in horizontal curves
- Accidents occur primarily at both ends of curves. Council (1998) notes that in 62% of fatalities and 49% of other accidents occurring in curves, the first manoeuvre that led to the accident 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 accident rates are observed. The majority of accidents on horizontal curves concern single vehicle run-off accidents and head-on collisions [86].

Horizontal curves of low radii lead to road safety problems, while the related risk rates increase significantly for radii < 200 m [73]. Research results show that the number of road accidents tends to increase when the radii of horizontal curves decreases [41][36]. The general form of this relationship, as confirmed from an exhaustive literature review by Hauer [39] is presented in the following Figure 2. 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 used small angles with sufficient sight distance [3].

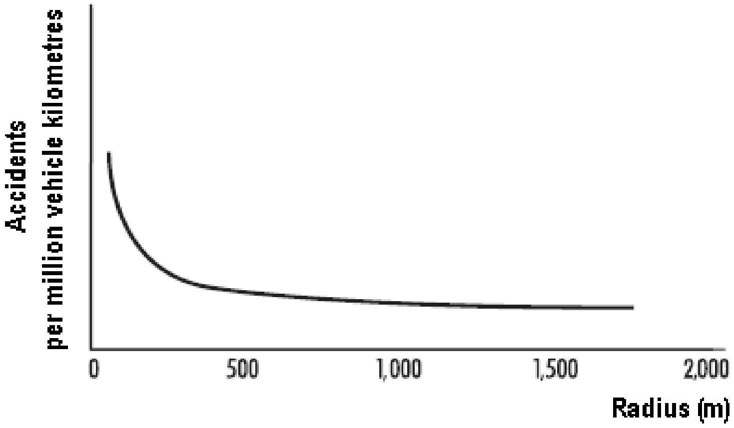


Figure 2 Effect of horizontal curve radius on accident risk (Hauer: 2000 PIARC 2003)

According to the above, transition curves (clothoides) are defined as a transition from a tangent (i.e. straight) section to a circular curve (i.e. the point where the radius of curvature reaches its minimum). In a transition curve, the road will gradually curve more and more. The design standards recommend that a transition curve should be constructed in horizontal curves, designed as a clothoide. A clothoide is a 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 [19].

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. In the following Table1, it is demonstrated that if a sharp curve is located on a road with low average curvature (i.e. long preceding tangents), accident risk increases significantly [56] [39]. Moreover, accident risk increases significantly with curve frequency [73].

	Accidents per million vehicle kilometres for preceding tangent length (m)							
Radius (m)	25	75	125	175	300	500	800	1200
126	0.33	0.36	0.48	0.41	0.53	0.25	0.55	0.64
286	0.15	0.21	0.20	0.26	0.23	0.20	0.23	0.31
489	0.22	0.17	0.77	0.22	0.11	0.21	0.05	0.17
812	0.21	0.07	0.12	0.06	0.15	0.12	0.08	0.10

Table 1. Accident risk breakdown by curve radius and preceding tangent length (Matthews, Barnes, 1988)

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 accident 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 [11] [83]. Graphs were drawn up to indicate the design quality of various possible curve radii sequences, as shown in Figure 3 below.

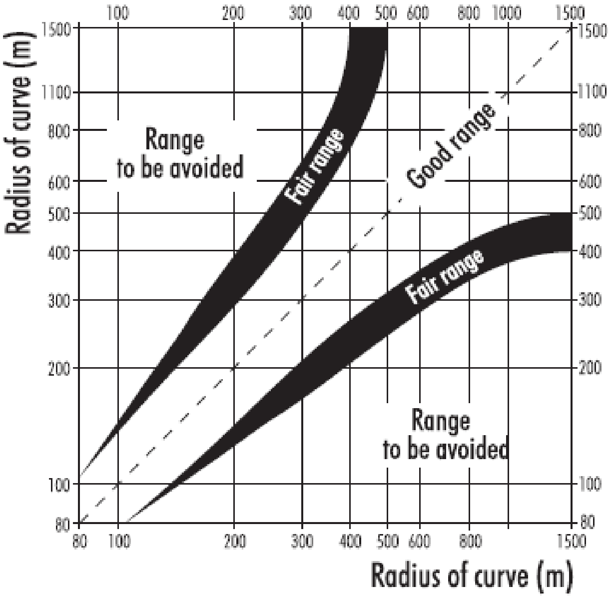


Figure 3 Tuning radii in curve sequences (Lamm et al 1999, RAS-L 1995)

Additionally, research results show that the proportion of vehicles run-offs at the external side of the curve increases when radius decreases, whereas on tangent sections around two out of three run-offs occur towards the right, probably due to vehicles attempting to avoid collision with vehicles coming from the opposite traffic stream [82].

Superelevation 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 laws of physics specify the relationship between speed, radius, superelevation and side friction. These laws can be captured by a simple mathematical formula, which can be used for design. As a result, the maximum speed in a curve increases with superelevation. Accordingly, using the maximum allowed superelevation and a "conservative" value for the side friction for various design speeds, one can compute the lowest "safe radius" [36] [46].

A transition zone between the tangent and the horizontal curve is needed to gradually introduce the superelevation. Dunlap, found the number of accidents on wet pavements to be abnormally high in curves with a superelevation of less than 2%. Zegeer report that improving the superelevation reduces the number of accidents by 5 to 10%.

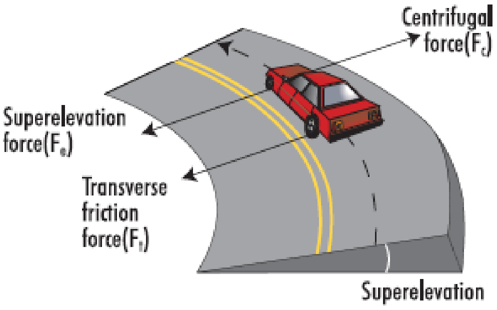


Figure 4 Horizontal curve system of force and superelevation (PIARC 2003)

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.

3.1.2 Vertical alignment

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 (Figure 5). The longitudinal section of a road includes sections with constant gradient and the related transition curves.

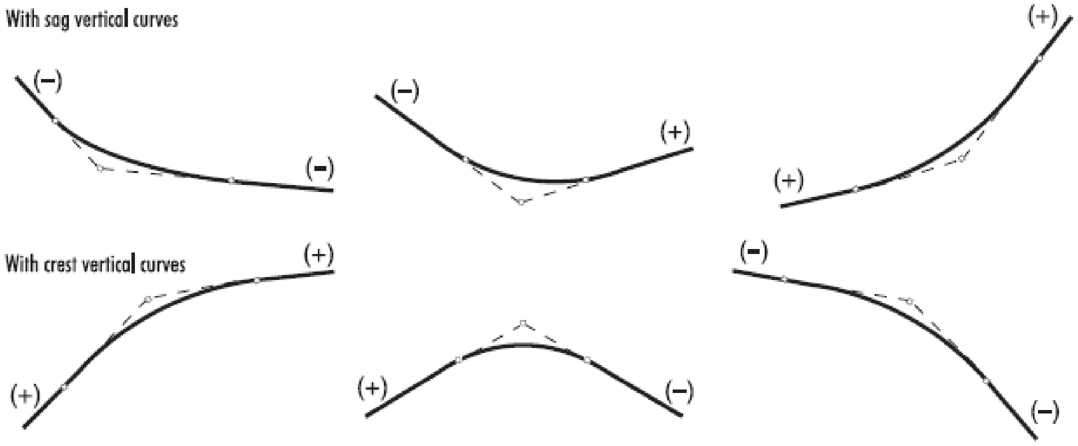


Figure 5 Examples of vertical alignment (PIARC 2003)

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

- Accidents occur more frequently on gradients than on level sections. Accident frequency increases with gradient percent [40]
- Accident 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 accident risk than the gradient percentage [80]
- A horizontal curve radius will be perceived incorrectly if the curve overlaps with a crest or sag vertical curve [35]. 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 accident risk [88] [10].

On **crest curves** of the longitudinal section, because of the limited radius of the transition curve, the available sight distance may not be sufficient for safe overtaking. It is important that values of the radius, for which appropriate overtaking distances are not assured, are avoided.

On **sag curves** of the longitudinal section, critical parameters include the range of vehicle lights, the presence of bridges or other constructions limiting sight distance. Other elements to be considered are water accumulation and accelerated erosion of shoulders due to water run-off.

A study on **vertical curves** has shown higher accident rates for sag curves than for crest curves. Moreover, according to a study [57], accident rates are higher when entering the curve than when leaving the curve, for both crest and sag curves.

The combined effect of road gradient and vertical curvature on accident risk was also examined by Matthews and Barnes [56]. The results were consistent with previous research and indicated that accident rates at sags and crests are very different and should not be considered similar. Moreover, it appears that the accident rate increases with the gradient on downhill sections (a 10% increase in accidents for every 1% increase of the downhill gradient is indicated), while it is not clear whether the accident rate increases with the uphill gradient. Finally, it is clear that higher radius vertical curves have a smaller accident rate than lower radius vertical curves [36].

3.1.3 Combination of horizontal and vertical alignment

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 [35].

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 (i.e. the horizontal curve may seem to have a higher radius than the actual), and may contribute to increased accident rates [81] [42].

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. The following results are a synthesis of the international experience, as presented in the "Handbook of Road safety Measures" [19].

- Increasing the radii of horizontal curves; straightening horizontal curves reduces the number of accidents when the initial radius of the curve is less than 200 m. According to some studies, the effect is even more significant the lower the initial radius of the curve [19]. In other studies, however, it has been shown that, adding x metres to the radius has the same effect on accident frequency regardless of whether the radius is 100 m or 1000 m [36]
- Constructing transition curves (clothoides); in curves with a given radius (i.e. a circular curve), a significant accident reduction can be achieved by constructing a transition curve, regardless of accident severity.
- Reducing the proportion of road length which lies in sharp horizontal curves; a road with numerous sharp curves is expected to have a higher accident rate than a road with fewer sharp curves. Reducing the proportion of road length which lies in curves of radius less than 500 m by around 5 percentage points would reduce the number of accidents by around 10%
- Reducing a road's degree of deflection; the degree of deflection reflects how much the road changes direction per unit of length. A road with high degree of deflection has many curves with small radius. A road with a small degree of deflection often consists of straight sections, but may have sharp curves between. However, reducing the degree of deflection of a road has

not been proved to have a positive effect on the number of accidents, probably because an unexpected sharp curve may be more surprising to drivers, and thus have a higher risk, whereas a sequence of sharp curves may lead drivers to a more cautious and conservative driving behavior.

- Increasing the distance between horizontal curves; according to the above, increasing the distance between horizontal curves is also not proved to have a significant safety effect, as curves after longer tangent sections may be more surprising to drivers.
- Reducing gradients; relevant studies show that reducing gradient reduces the number of accidents (both injury and material damage accidents). The higher the gradient is, the more significant the accident reduction
- Reducing the proportion of road length which lies in sharp crest curves; the measure aims at reducing the proportion of road with limited sight distance, as at sharp crest curves. However, the results of the few available studies do not indicate a significant effect on road accidents, probably because of the fact that drivers take into account the limited sight distances on crest curves and adapt their driving behavior accordingly.
- Reducing the proportion of road length which lies in sharp sag curves; sag curves do not cause visibility problems, however increased speeds when entering sag curves from downhill may be a risk factor. The results of the few available studies do not confirm that reducing the proportion of road length which lies in sharp sag curves reduces the number of accidents.
- 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 accidents, as the improved sight distance may cause higher speeds of vehicles.
- Removing visual obstacles along the roadside

3.2 Cross-sections

This section summarizes the known relationships between accident experience and cross-sectional roadway elements. Such elements include lane width, shoulder width, shoulder type, roadside features, median design, and others [109].

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 a certain improvement of road safety. However, very large lanes may lead to important increase of travel speeds.

Research results have shown that accident risk decreases when lane width increases. Results for two-lane roads indicated that increasing lane width beyond 3,3 m may not be justified in terms of road safety benefit [45][42][36].

The implementation of a shoulder (especially paved) or an emergency lane also contribute to improved road safety on interurban roads [67]. Research results indicate that very narrow shoulders (e.g. <0,5 m) or very wide emergency lanes (e.g. >3 m), which may end up being used by drivers as regular lanes in increased traffic, are related to increased accident rates [42].

Moreover, research results have shown that accident risk decreases when shoulder width increases. Results for two-lane roads indicated that increasing shoulder width beyond 2,5 m may not be justified in terms of road safety benefit [45] [105].

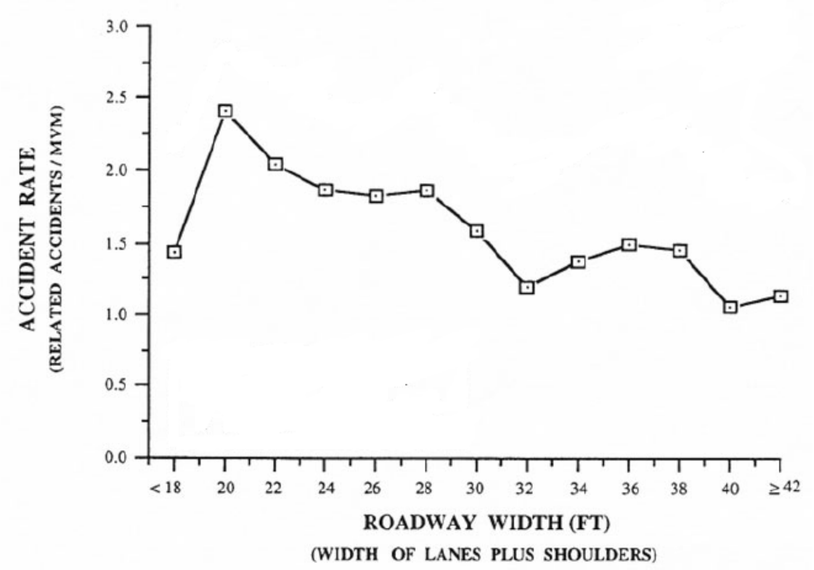


Figure 6 Effect of roadway (lane plus shoulder) width on accident risk of two lane low volume rural roads (1 ft=0,305 m) (Zegeer et al 1994)

The construction of a median on interurban roads may contribute significantly in reducing the number and severity of road accidents. On roads with more than two lanes, the implementation of a median leads to significant reduction of the number of road accidents. However, accidents still occur, because of drivers crossing the median and entering the opposite traffic stream. The number of these accidents decreases when median width increases. For median width equal to 12 m, only 15% of vehicles that enter the median also enter the opposite traffic stream [29].

Moreover, it has been found that an important decrease of the reduction rate of accident risk is observed for median width beyond 6-7 m On single carriageway roads (undivided roads), it is recommended to have sufficient cross-section width, to allow for overtaking without entering the opposite traffic stream. Additionally, on uphill sections, where heavy vehicles have low travel speeds, it is recommended that additional idling lanes are foreseen. 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 sections **cross-slopes** mainly serve for the drainage of the carriageway. The lower the transverse gradient, the more increased is the probability of water concentration on the carriageway, and consequently the higher the probability of accidents due to skidding, as shown in Figure 7. On horizontal curves, it is important to select appropriate superelevation. The lack of appropriate cross-slope/superelevation may increase accident 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 [19]:

- 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 accidents.
- Increasing road width; an increase leads to a reduction in the number of both injury and

damage accidents in rural areas. However, in urban areas, a corresponding increase of road width lead to an increase in the number of accidents

- Increasing lane width; the measure appears to have the same effect on injury accidents as increasing the width of the road.
- Increasing shoulder width, which can also reduce the number of injury accidents, 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 accidents. However, medians on two-lane rural roads may increase the number of accidents.
- Increasing median width; in general, the measure results in accidents reduction.

3.3 Junctions

Junctions, at-grade or grade separated, are locations of high accident concentration. In most countries 40 - 60% of the total number of accidents 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.

3.3.1 Road safety criteria in junctions design

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) [28].

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 [100].

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 accidents at these points.

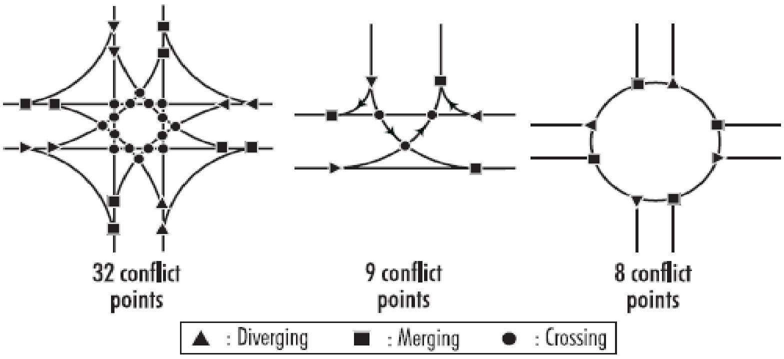


Figure 7 Number of conflict points at junctions and roundabouts

- Sufficient sight distances: Appropriate sight distances, both while approaching the junction area and being at the junction are of major importance for the safe operation of the junction. The creation of junctions in vertical sag curves is considered to be favorable. Another important parameter concerns 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 therefore the selection of appropriate path and travel speed, on which drivers can be assisted by improved horizontal and vertical road marking and appropriate junction layout [49].
- Longitudinal section and transverse gradients design: It is important to design the longitudinal section of the road in the junction area and access areas, in order to achieve a smooth transition of transverse gradients and effective drainage. Ideal location for a junction is on a tangent. Location in curves may cause problems, as visibility is reduced, conflict points increase and superelevation and lane widening make the situation more complicated. Moreover, 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 [70]
- Left turning movements: The locations where left turns and U-turns are allowed should be specifically determined and appropriately configured, by means of traffic islands and/or marked lanes. It should be noted that left turns are high risk movements on a level junction. Research results in Great Britain have shown that these movements (right turns in Great Britain) are responsible for around 70% of all accidents on three-arm junctions [89]
- Minimization of weaving areas

3.3.2 Effect of junction type on road safety

The choice of a junction design depends upon several factors, whose relative importance varies between cases and should be assessed. The most important ones are [70]:

- 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 neighboring 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 8 shows guidelines for the selection of junction type according to traffic flows.

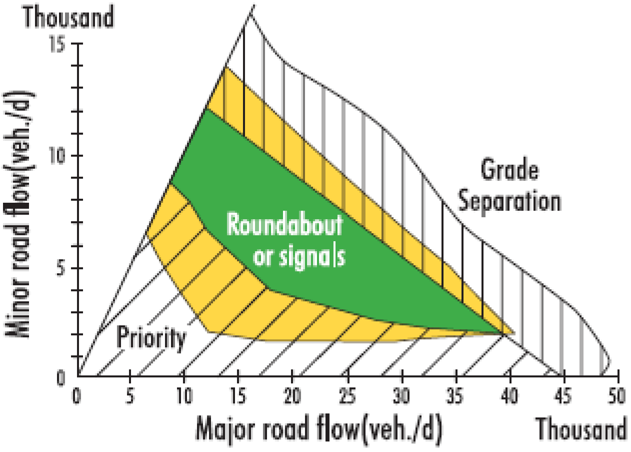


Figure 8 Type of junction based on traffic flows (IHT 1997)

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 [59]. 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 30% accidents reduction [91].
- 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 [63]. However, in some countries they appear to be related to higher accident involvement of motorized two-wheelers and bicycles [92].

Converting junctions to roundabouts can improve safety and traffic flow. Roundabouts can contribute to road safety in the following ways [19]:

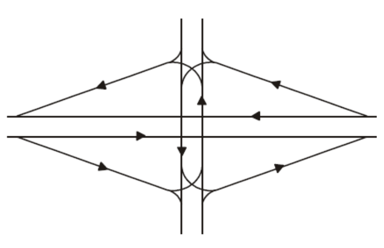
- Conflict points between the traffic streams are theoretically reduced
- Roads users entering the roundabout have to yield to road users already in the roundabout, thus they are forced to observe traffic at the roundabout more carefully
- All traffic comes from one direction
- Left turns are eliminated
- 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 accidents 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 accidents and serious injury accidents are reduced more than slight injury accidents [19]:

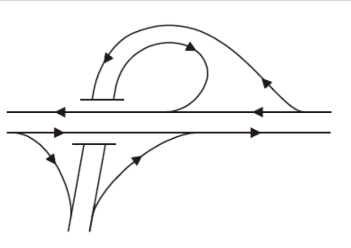
- Signalized junctions. Signalized level junctions are the most common junction type in urban areas. Fatal accidents at signalized junctions are predominantly multivehicle [4]. The majority of accidents on signalized junctions concern left-turn vehicle movement or pedestrian's movement. Moreover, a higher accident involvement, in relation to their traffic volumes, may be observed for motorized two-wheelers and bicycles [92].

- Grade separated junctions (interchanges). These junctions present lower accident 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% accidents reduction, while the respective percentage for a four-arm junction may reach 75%.[89]. However, for the safe operation of a grade separated junction, an efficient planning is required. For example, research results have shown that reducing the number of lanes in the junction area, or designing weaving length of less than 1 km, may have negative safety impact. Moreover, accident rates on the arms of the grade separated junctions are about higher compared to the sections outside junction. Additionally, accident severity rates on junction arms are higher compared to the related rates for interurban roads (not characterized as motorways) [87].

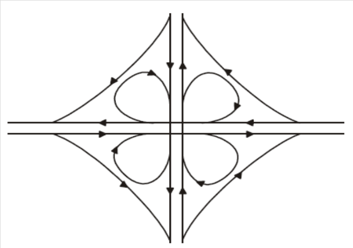
There are different forms of grade separated junctions (interchanges). In full grade-separated interchanges, with separate lanes for all streams of traffic, all movements which require crossing other streams of traffic are removed and reduced to changing traffic lanes. Various forms of interchanges have been developed, such as diamond interchanges, trumpet interchanges and full or partial cloverleaf interchanges. Diamond interchanges (simple and comprehensive, with straight ramps, and with minor roads running above the main road) appear to be the safest form of interchange.



Diamond



trumpet



cloverleaf

The effect on traffic safety from replacing a level junction with a grade-separated (interchange) has not been fully determined. If accidents on crossroad arms of a length corresponding to the length of the ramps in interchanges are included in accident figures, then interchanges are safer than both three- and four-arm junctions. However, ramps constitute a new road element in interchanges, and therefore accidents on stretches of road of equivalent ramp length at junctions should not be included in accident figures for junctions.

Effectiveness of junction treatment

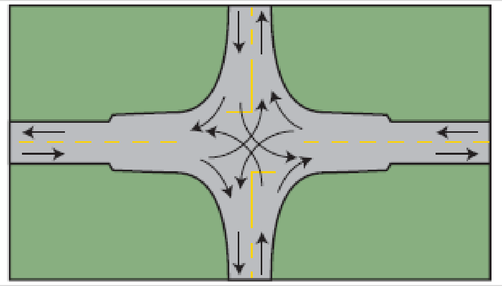
Channelization

- 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

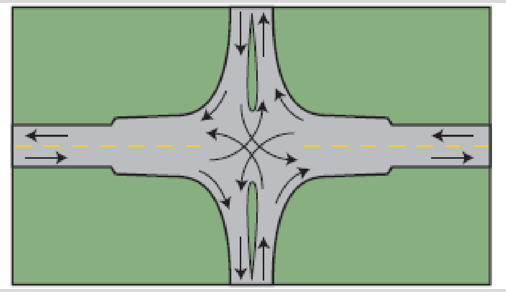
It can be carried out by using traffic islands (physical channelization or road markings (painted channelization) and can include:

- Minor road channelization

- Left-turn lanes
- Passing lanes
- Full channelization



Unchannelized crossroad



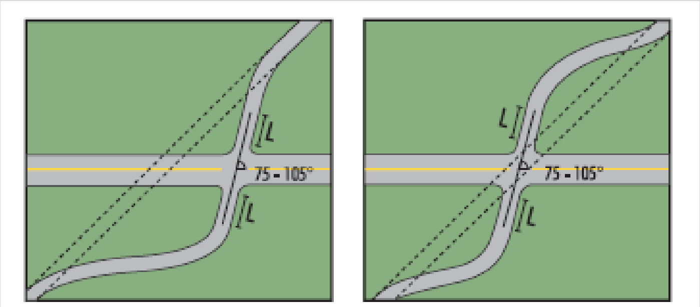
Channelized crossroad

The majority of the various forms of channelization appear to have a more favourable effect on the number of accidents 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 accidents.

Redesigning junctions

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

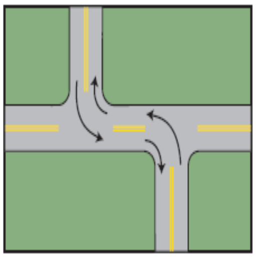


Examples of junction re-alignment

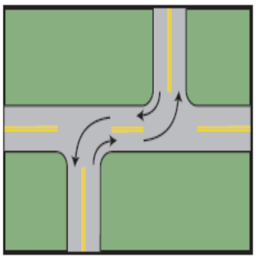
Research results are very uncertain, however it can be deduced that an angle of less than 90 degrees gives the fewest injury accidents and the opposite appears to be the case for property damage only accidents. Moreover, a change in gradient on approaches to an junction from more than 3% to less than 3% appear to reduce the number of injury accidents, but increase the number of damage only accidents. 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 accident 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.



Left - right staggering



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 accidents may be significantly reduced.

3.4 Other Design Elements

3.4.1 Lighting

Sufficient lighting of roads and junctions can reduce accident risk at night. Around 35% of all reported accidents occur in the twilight or in the dark. The percentage is the same both inside and outside urban areas. The percentage of accidents in the dark is also higher for accidents involving pedestrians and accidents concerning vehicles run off the road [19].

The objective of road lighting is to reduce the accident 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 necessary according to priority 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 accidents in the dark [98]. Moreover, the effect of road lighting has a greater effect on accidents involving pedestrians in the dark than on other accidents. Additionally, the effect of road lighting does not vary significantly among different road environments (motorways, urban and rural areas). Improving existing lighting also has a significant safety effect, by reducing the number of road accidents.

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.).

3.4.2 Roadside

Accidents occurring on the roadside, as a result of vehicles run off the road, are an important proportion of the total number of accidents. Constant obstructions (may cause significant injuries when such accidents occur. Roadside treatment aims at minimizing the probability of accident, through appropriate roadside configuration (roadside design, land use etc.) and limitation of constant obstructions. In case a vehicle runs off the road, the higher the roadside free zone is, the higher is the probability than the accident is avoided [70] [69].

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.

Different restraint system designs utilize different levels of containment (e.g. N2 barriers will deflect cars but can be breached by heavier vehicles), and different working widths. Choice of type and siting of restraint systems to use 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 N2 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.

4. Managing safety of roads through their whole life

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.

4.1 Management processes

Four groups of analysis tools have been developed to cover the different stages of the road life.

4.1.1 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 [21]. 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 accident 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).

The European Commission has prepared guidelines requiring safety impact assessments to be carried out on all new projects for the Trans-European Road Network.

4.2 Safety audit of initial design and construction

Investigation of accidents occurring after a road has been built often indicate deficiencies in design that could have been eliminated at the design stage [1]. 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 [42][94][14][6][7][61]. An extensive account of the practical issues associated with auditing is provided by Proctor [71].

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.

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 accident savings that would result from proposed modifications at the audit stage [104] [78] [7]. Transit New Zealand [94] has shown that the benefit to cost ratio of audits average typically between 10:1 and 20:1 [21].

4.3 Regular accident reduction remedial treatment

Road authorities are required to operate their roads safely. To do this it is necessary to monitor accident occurrence and to assess the scope for remedial treatment to reduce accident numbers and severity. This is most effectively done by maintaining an accident investigation and reduction team [42]. These teams are able to consider four types of treatment - black spot treatment at individual 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 accidents have occurred in the past.

Countries with large numbers of accident black spots are likely to focus initially on treatment of individual sites. Good analysis methods are required to ensure budgets are correctly targeted – an example of Polish materials is given in Szczuraszek [83]. Low cost engineering solutions can produce high benefits at these sites [20]. As an accident reduction programme matures and accident 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.
Accident investigation requires a combination of detailed analysis of accident data and on-site investigation.

Example of accident 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 accident rates because drivers perceive their risk as different. Detailed analysis of accident reports are therefore needed to diagnose the causation factors. Site inspections are focussed on those road sections with high number of accidents 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 accident improvement programmes it is important both to monitor the overall trend in accidents 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 accident numbers 3 years before and after the treatment. No attempt is made to describe site conditions in detail or to correct the difference in accident 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 [32].

4.3.1 Audits of existing roads

Where historical accident 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.

Safety audit of existing roads in France
Machu [54] describes a survey of roadside treatment over 2500 kms 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 [96] and this work has been extended to assess ways of providing more forgiving urban roadside environments [97].

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 is developing 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 accident 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 accident occurrence ratings within the overall assessment [51].

4.4 Assessing the value of investment in road improvement

The returns from low cost engineering measures have generally been justified in terms of the first year rate of return from comparing the value of accident savings in that year with the cost of the treatment. Accident savings are so high [20] that more detailed analyses are not necessary.

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 [70] 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 accident reduction discounted over the life of the project should be compared.

4.4.1 Road and pavement maintenance

Friction is defined as the resistance to motion between two surfaces in contact. Its magnitude is expressed by the coefficient of friction (f) which is a ratio of 2 forces, one parallel to the surface of contact between two bodies and opposed to their motion (the friction force) and the other perpendicular to this surface of contact (the normal force).

In the context of road transportation, the surface of contact is the road-tire interface and the normal force is the wheel load. The coefficient of friction ranges from nearly 0 under icy conditions up to above 1.0 under the best surface conditions [70].

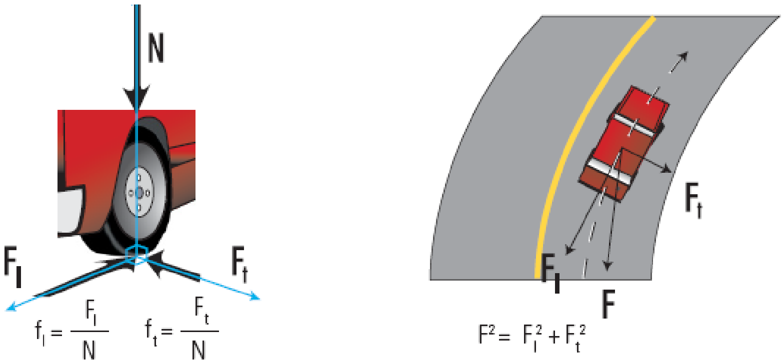


Figure 9 Longitudinal and transverse friction

Longitudinal friction concerns the friction on the direction where a vehicle is moving and affects acceleration and deceleration. Transverse friction concerns the available skid resistance at a direction which is perpendicular to the vehicles direction of travel, and allows for change of direction.

The skid resistance of a road pavement is an important road safety factor, especially when the road surface is wet. A concentration of accidents on a wet surface can therefore be an indicator of friction deficiency. The following conditions increase the risk of accidents even more:

- The problem is at a location where the friction requirement is high (e.g. approach to an junction, horizontal curve, downhill slope);
- 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 accident risk due to skidding and the pavement's skid resistance. Accident 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, accident risk is 300 times higher [90].

The accident risk is higher when the skid resistance is low. Accidents 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 accidents are worst at road locations having both a poor skid resistance and a high friction demand:

- Page and Butas (1986) found that accident rates on wet pavement were highest in horizontal curves, especially when SFC was less than 0.25. Wet pavement accident rates were also higher for both uphill and downhill slopes (steeper than 3%) than for flatter terrain.

- Farber et al (1974) report that only 2.3% of wet surface accidents occurred on tangent sections of roads, where the friction demand is low.
- Viner et al (2005) concludes 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.

There exist sufficient studies to indicate that 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 [60]. However, the most important factor affecting skid resistance is pavement macrotexture, which is the feature that increases skid resistance at high travel speed. Results in Great Britain indicated that accident risk increases when texture depth drops below 0,7mm [93]. Similarly, in a study of crashes and surface characteristics on open roads in France, it was found that wet weather accidents increased markedly for sand patch texture depth less than about 0.5 mm, as shown in Figure 10.

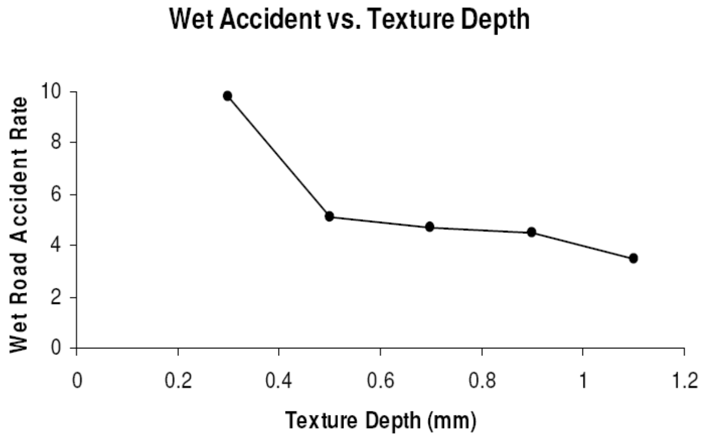


Figure 10 Relationship between Wet-Accident and Surface Texture Depth (Gothie 1991)

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 [70].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 accidents. 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 [70].

The safety impact of pavement roughness varies according to the type of accident considered [2]:

- The single-vehicle accident rate decreases as the pavement roughness increases, due to reduced speeds;
- The multi-vehicle accident 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.

5. Roads need to cater safely for all users

Road design should reduce the probability of accidents in advance, by means of the infrastructural design, and where accidents do occur, the process which determines the severity of these accidents should be influenced such that the possibility of serious injury is virtually eliminated. Thus, a sustainable, safe traffic system has [72]:

- 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 [95].

5.1 Pedestrians

Pedestrians form the second largest group of road casualties (after car occupants). They account for about 15% of the road fatalities in the European Union. The over-55 and under-12 age groups are those with the highest risk of becoming pedestrian casualties. In most countries, accidents involving pedestrians (apart from those resulting in fatal injuries) tend to be underreported [72].

Design principles and measures for improving pedestrian safety include [72]:

- 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

5.2 Cyclists

The number of cyclists killed per cycled kilometre is very much influenced by the total number of cycled kilometres. The accident risk based on the amount of cycling is lowest in Denmark and the Netherlands (resp. 15.9 and 17.6 fatalities per billion km). The risk is particularly high in France and Great-Britain (resp. 67.7 and 52.5), 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 [72].

When facilities for cyclists are being designed, five criteria are important if their needs are to be met [72]

- 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 [72]:

- 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 [72]:

- 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.

5.3 Motorized two-wheelers

Motorcycle and moped fatalities in western European together represent 10-15% of all traffic fatalities. For both mopeds and motorcycles, the rate of fatalities per 10^5 vehicles is much higher for younger riders than for older riders. The percentage change in fatality rates per 10^5 vehicles shows a positive trend between 1990 and 1995. Only Ireland and Greece exhibited increasing fatality rates in these five years. All other countries had fatality rate decreases of between 20 % and 55% [72].

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.

Taking care of the needs of motorized two wheelers fits into a non restrictive approach. However, speed reduction measures also have to be reviewed to better guarantee that riders of motorized two wheelers keep to the limit. Another aspect of a non-restrictive approach is to consider special traffic rules for motorized two-wheelers to provide the riders of these vehicles with some privileges. More use of two-wheelers may contribute to the solution of congestion problems. Examples of privileges are the possibilities of overtaking slow moving lines of cars and riding on lanes with limited access. Insofar as such lanes separate motorcycles/mopeds from cars, they could improve safety of these vehicles. On the other hand, it is also important to separate motorcycles and mopeds from cyclists and pedestrians.

Particular attention may need to be given to the design of safety barrier systems at sites where there is a high risk of two-wheeled vehicles leaving the road.

5.4 Young drivers

It can be seen that in almost all European countries road accidents 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 accidents than older riders and drivers [72].

It can be seen that in almost all European countries road accidents 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 accidents than older riders and drivers [72]
Several characteristics of young drivers that are related to traffic engineering countermeasures can be identified [25]:

- 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 maneuvers 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.

5.5 Elderly

In many Countries the fatality rate for elderly people on the roads is about 1.5 times the average. Older drivers do, however, have lower exposure. In 2003, road accident fatalities among over 65s comprised around 18% of all road accident fatalities. This equates to 11,000 fatalities in a year and about 30 fatalities each day [18].

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 [95].

Research results [9] 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
- Maneuvering at weaving areas (e.g. at-grade junctions)

- Benekohal [9] 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 [58].

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