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# Traffic safety principles and physical road infrastructure measures

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## ABSTRACT

With the aim of facilitating a comparative functional analysis of driving assistance systems and infrastructure measures for traffic safety, this paper studies the underlying concepts of safe road design, and derives a general set of traffic safety principles. Road categorisation is studied as an important parameter for both road design and route selection that are optimised from a traffic safety perspective, and an extended road categorisation is proposed. Finally a systematic overview of infrastructure measures is provided, as a basis for a future comparative functional analysis.

*Keywords:* traffic safety, traffic safety principle, road categorisation, road function, infrastructure measures

## INTRODUCTION

One of the main instruments for improving road traffic safety concerns the implementation of specific infrastructure elements following the concepts of sustainable road traffic safety [Koornstra et al. 1992], traffic calming [UK Parliament 1992] and zero tolerance concerning fatalities and serious injuries [Tingvall 1997], which developed since the early 1990's, especially in The Netherlands, the UK and Sweden. Another major instrument with great potential that developed during the past decade concerns the implementation of driving assistance systems [Lu et al. 2005]. These systems may often act as substitutes or complements for infrastructure measures [Lu et al. 2003]. Therefore, a thorough understanding of infrastructure measures and the underlying concepts may help to study, assess and evaluate potential traffic safety impacts and benefits of implementing driving assistance systems.

The objectives of this paper are to review and analyse the concepts and basic principles of safety focused road design, and to identify an extended, more general set of traffic safety principles, that covers the functional aspects of both infrastructure measures and driving assistance systems. Also the topic of road categorisation is addressed, as different road categories involve different types and levels of traffic risk, and a specific infrastructure measure often relates to and is designed for a specific road category, while the definition of an adequate safety focused road categorisation is useful for research on selection of optimal routes from a traffic safety perspective. An alternative road categorisation is proposed based on an analysis of three existing ones. Furthermore, a systematic overview is given of identified infrastructure measures, providing a solid basis for a future comparative functional analysis of driving assistance systems with infrastructure measures.

## CONCEPT OF ROAD TRAFFIC SAFETY

Since the late 1980's there was a growing interest, in The Netherlands and elsewhere, for road layout design as a specific measure to improve traffic safety. This can be seen as one of the stages in an evolutionary path of different consecutive sets of measures to improve traffic safety. A next set may evolve when a previous set becomes less effective due to the law of diminishing returns, and may be based on new insights or knowledge, a change of priorities, or availability of new technologies. The increased focus on infrastructure, like in the Dutch concept DVI ("Duurzaam Veilige Infrastructuur" - sustainable safe infrastructure), is embedded in a continued attention for other measures with a longer history, such as education and enforcement. And although some of the infrastructure ideas are to a certain extent innovative, also part of it can be characterised as "old wine in new bottles". It is especially the thinking about the principles of road layout design from a specific traffic safety perspective, and a large-scale systematic and standardised implementation that are innovative. The implementation itself is largely carried out with structural elements that exist already for a long time, such as roundabout or speed hump.

The Dutch concept "Duurzaam Veilig" (sustainable safe) originated in the early nineties [Koornstra et al. 1992, p.9]: "In a sustainable safe road traffic system the risk of accidents has been drastically reduced a priori by the design of the infrastructure. As far as accidents still happen, the process that determines the severity of the accidents is conditioned in such a way that serious injury is practically excluded." It is further stated that such a system at first sight may seem rather utopian, that it, however, might be realised by defining for the road traffic system the same safety requirements as for newer technologies like nuclear power stations, refineries, air traffic and rail transport. An important underlying principle is that the human, who can make mistakes, is the measure of things [Koornstra et al. 1992, p.15]. Road traffic is the result of the interaction between humans, vehicles, road infrastructure and regulation. In this process the human is a key (and determining) element, but it is also the weakest link, in terms of both behaviour and vulnerability. It was recognised that human error is a major factor in road accidents and that it is difficult to achieve permanent changes in human behaviour [Evans 2004]. Therefore, the concept aims at prevention of accidents, and at minimising the effects of accidents if they happen. Its three principles are (1) to prevent unintended use of the road infrastructure (i.e. use not corresponding with the intended function); (2) to prevent insecure and ambiguous behaviour of road users; and, especially (3) to prevent encounters of road users at high differences in speed, direction and mass. According to Koornstra, et al. [1992] the key to achieve a sustainable safe road system lies in the systematic and consistent application of these three safety principles, which also can be formulated in a positive sense as: induce and promote a use of the road network that is functional, predictable and homogeneous. In [Schermers & Van Vliet 2001] a sustainable safe traffic system is defined as comprising: (1) a road environment with an infrastructure adapted to the limitations of the road user; (2) vehicles equipped with technology to simplify the driving task and provided with features that protect vulnerable and other road users; and (3) road users that are well informed and adequately educated.

In a document on the categorisation of roads according to the principles of sustainable safety [CROW 1997, p.6], which forms a basis for the implementation of the DVI Programme in The Netherlands, the concept is elaborated in some more detail. The concept "sustainable safe" is described as "a systems approach of the traffic safety problem. Within that system all elements (e.g. function, design, regulation and use) need to be tuned to one another. Sustainable safe and functional use of the road network takes into account route selection, vehicle types, traffic flow, accessibility and intensities. By appropriate design and traffic rules, a regular traffic flow can be achieved, and low speeds at crossings be enforced.

Predictable traffic behaviour can be achieved by recognisable and simple traffic situations, and willingness of road users to accept traffic rules." This description is in essence not different from, and partly complementary to the previous one. It does not explicitly mention the elements risk, consequence, and human error, but provides a more operational description. Both definitions focus on infrastructure design. The aforementioned three principles are then restated as three concepts: road network functionality, traffic homogeneity and traffic behaviour predictability. Functionality of the road network can be improved by defining and implementing clear and easily recognisable road categories, which is thought to help induce intended behaviour of road users. Homogeneity of the traffic is increased by allowing only limited differences in speed and direction between road users, and between road users and obstacles. Predictability of the behaviour of road users can be improved if route choice and the necessary manoeuvres are always and everywhere simple (i.e. not complex) and understandable for all road users.

A similar increased focus on infrastructure and similar concepts developed in other countries in the same time frame, notably in the UK (traffic calming [UK Parliament 1992]) and in Sweden (Vision Zero [Tingvall 1997]). These concepts are made more operational in the following statement. The layout of the infrastructure should inform the driver in a natural and implicit way about intended use and expected behaviour, and help to prevent encounters at large differences in speed and direction, by implementing the following speed rules [Pasanen 1992; Tingvall & Haworth 1999]:

1. never mix motor vehicles with other slower forms of traffic at speeds higher than 30 km/h;
2. never have level road crossings with speeds higher than 50 km/h; and
3. never have opposite traffic without separation at speeds higher than 70 km/h.

**Table 1** Categorisation of traffic safety requirements according to application area for infrastructure measures (after [CROW 1997])

#	requirement	applicable to	network	routes	road sections	inter-sections	category transition
1	create large-size continuous residential areas		x				
2	minimise journey on relatively unsafe roads		x				
3	make journeys as short as possible		x				
4	let shortest and safest route coincide		x				
5	prevent search behaviour			x		x	
6	make road categories recognisable			x	x	x	x
7	limited number of standard traffic solutions			x	x	x	x
8	prevent conflicts with oncoming traffic				x	x	
9	prevent conflicts with crossing traffic				x	x	
10	separate traffic categories				x	x	
11	reduce speed at sites of potential conflict				x	x	
12	prevent obstacles along the carriageway				x	x	

Clearly, for implementation of DVI an adaptation of the road network layout is needed. To make the concept more operational for this purpose, the DVI principles for a safe road infrastructure are translated in [CROW 1997] to a set of twelve requirements for an inherently safe road network, which are respectively related to (see Table 1): network structure (requirements 1 to 4), selection of routes within the network (requirements 5 to 7), layout of road sections (requirements 6 to 12), layout of intersections (requirements 5 to

12), and category transitions (locations in the road network where different road categories connect; requirements 6 and 7).

Two related concepts were developed during the 1990's: self-explaining roads and forgiving roads [Janssen et al. 1999; Lu 2006]. Self-explaining roads have a recognisable road layout dependent on the road category, with the aim to induce adequate driving behaviour (i.e. according to the traffic regulations, thereby preventing hazardous situations and accidents due to behaviour against these regulations), thus making driving safer. Forgiving roads have structural layout elements that interfere with or block the development of driving error, correct driving error and mitigate the consequences of accidents once they happen. Self-explaining road design aims to reduce accident risk by preventing human error, while forgiving road design aims to reduce accident risk by correcting human error, and to mitigate accident consequence.

## TRAFFIC SAFETY PRINCIPLES

The twelve requirements focus on prevention and mitigation of the effects of conflicts between vehicle and vehicle, vehicle and other road users, and vehicle and obstacles, while not all possible conflicts in these categories are covered (e.g. prevention of collision with coincidental obstacle on the road), and especially single-vehicle situations are missing. These include single vehicle roll-over and single vehicle run-off road incidents, due to loss of lateral control or wrong manoeuvring, and inappropriate speed when the vehicle approaches a curve. In addition, the principle of error forgivingness is missing. This implies that these safety requirements do not cover all measures based on infrastructure and driving assistance systems. Therefore, and based on the aforementioned concepts of sustainable safety, we identify an extended set of five basic traffic safety principles, as fundamental components of traffic safety, with no or minimal overlap, and covering the major functional aspects of traffic safety measures related to infrastructure design and driving assistance systems. Alternative terms for (traffic safety) principle are (traffic safety) feature, parameter, determinant or vector (amongst other possibilities). For each traffic safety principle several more operational sub-principles or traffic safety requirements are identified. The traffic safety principles are listed and described below, while for each principle the related traffic safety requirements are indicated.

### Traffic safety principle 1: road network functionality

The structure and layout of the road network should be functional. Functional use of the road infrastructure should be encouraged and induced, and unintended use should be prevented. This principle addresses road network layout and use at a more global level, i.e. at the network level. It has both objective aspects, that inherently generate functional behaviour (as other behaviour is not possible), and subjective aspects, that should induce functional behaviour of the driver. This principle covers part of the idea of self-explaining roads at the global level. Related traffic safety requirements are the items 1, 2, 3 and 4 listed in Table 1.

### Traffic safety principle 2: recognisability and predictability

The road environment should be adapted to the limitations of the road user, and should be informative about expected behaviour. Complex traffic situations should be avoided, and everywhere route choice and necessary manoeuvres should be fully comprehensible for every road user. Recognisability of the traffic situation should induce predictable behaviour,

and prevent insecure and ambiguous behaviour. An important precondition is willingness of road users to accept and behave in accordance with the rules set by the traffic regulation. This principle addresses road layout and use at a local level, i.e. at the level of the traffic situation that the road user encounters. This principle covers the other part of the idea of self-explaining roads, i.e. at the local level. Related traffic safety requirements are the items 5, 6 and 7 listed in Table 1.

### **Traffic safety principle 3: traffic homogeneity**

Homogeneous use of the road network aims at preventing encounters between road users, and between road users and obstacles, at high differences in speed, direction and mass. This principle is rigorously expressed in the three speed rules [Pasanen 1992; Tingvall & Haworth 1999] (see Section "Concept of road traffic safety"). Related traffic safety requirements are the items 8, 9, 10, 11 and 12 listed in Table 1.

### **Traffic safety principle 4: driving task simplification**

Simplifying the driving task and thereby reducing driver workload is a way to enhance the capability of the driver. This principle at first sight resembles one aspect of the principle "recognisability and predictability", i.e. making traffic situations simple (avoidance of complex traffic situations), but even though a simple traffic situation simplifies the driving task, it is in fact different. This principle does not focus on the ad-hoc traffic situation but on the continuous process of driving. It aims at taking away some of the effort that is needed for driving, and/or at reducing the needed attention for certain parts of the driving task, and/or at helping to take correct decisions in certain situations. Related traffic safety requirements are the items 13 "driver capability enhancement" and 14 "driver workload reduction" (the numbering of these items expands the numbering of the items in Table 1).

### **Traffic safety principle 5: error forgivingness**

Despite implementation of the foregoing four principles, drivers will continue to make errors, because of the limitations of the human being. This principle focuses on: (1) correcting driving errors at an early stage, when they start developing, by interfering with or blocking the development of the error; and (2) mitigating consequences of driving errors once they have developed too far and a conflict cannot be avoided anymore. Related traffic safety requirements are the items 15 "error correction", and 16 "consequence mitigation".

## **ROAD CATEGORISATION**

For several reasons functional road categorisation (or classification) is a relevant topic for road traffic safety: (1) different road categories involve different types and levels of traffic risk; (2) a specific infrastructure measure often relates to a specific road category; (3) implementation of road categories with clear and recognisable characteristics improves road network functionality, and thereby helps to induce intended road user behaviour; (4) different road categories require a distinct design of the road environment to satisfy the requirements of self-explaining and forgiving nature; (5) road categories play a role in the above mentioned sixteen requirements (especially in requirements 2, 4, 6 and 7); (6) road categorisation is used for a long time in urban planning [Buchanan 1964] and by urban traffic planners (see, for instance, the yellow urban arterials on standard paper city maps); and (7) road categorisation in digital maps for in-vehicle applications is an important

attribute for route selection in navigation systems, which may contribute to traffic safety (i.e. selection of safer routes). In addition, road categorisation is an essential element for analysing the functional relationships of infrastructure measures and in-vehicle driving assistance systems [Lu et al. 2003]. Three different functional road categorisations are discussed in the following sub-sections: (1) the categorisation used in DVI; (2) the FHWA categorisation used in the USA; and (3) the categorisation used in digital map databases for in-vehicle systems. From this discussion a road categorisation will be proposed with a granularity that better accommodates the reality of the road network, and is more suitable for traffic safety purposes.

## Functional road classification in DVI

An important element of DVI is the distinction of three different road categories according to their function: flow roads, collector roads and local access roads, and the definition of their characteristics. That such categorisation makes sense becomes clear from Table 2, which shows significant differences in traffic risk on different road types. Note that these road types are different from the three road categories just mentioned.






**Table 2** Road accident injury rates in the Netherlands on different road types (after [Wegman 2003] and [Schermers & Van Vliet 2001])

road type	speed limit (km/h)	mixed traffic	intersecting / oncoming traffic	injury rate per 10 <sup>6</sup> km	
				1986	1995
residential areas	30	yes	yes	0.20	0.15
urban street	50	yes	yes	0.75	0.73
urban artery	50 / 70	yes / no	yes	1.33	1.27
rural road	80	yes / no	yes	0.64	0.51
express road / road closed to slow vehicles	80	no	yes	0.30	0.28
motor road	100	no	yes / no	0.11	0.08
motorway	100 / 120	no	no	0.07	0.05

In the definition of DVI [Koornstra et al. 1992; CROW 1997], roads of the highest category, *flow road* (literal translation from Dutch: "stroomweg"; also translated as "through road"), have a through or flow function, and are intended for continuous circulation of motor vehicles at high speeds. They require separate carriageways, absence of crossing traffic, and connection with the rest of the network exclusively via slip roads (only merging and exiting traffic). In practice, this is a motorway (in Dutch: "autosnelweg"; in US English: "freeway"). Roads of the lowest category, *local access road* (in Dutch: "erftoegangsweg", literally "premises access road"), are intended to provide access to residential areas (which are here meant to include shopping areas and mixed residential/shopping areas of a similar setup; an alternative term is "sojourn areas") for all modes of transport (such as pedestrians, bicycles, mopeds and motor vehicles), and to facilitate getting into and out of vehicles, loading and unloading of goods, and manoeuvring. Because of the mixed character of the traffic, the maximum speed should be low everywhere. In between these two categories a third one is defined, with two functions, flow and exchange, which are separated in location. Exchange takes place at intersections, while flow is possible on the road stretches between intersections, ideally with separation of traffic modes. These roads facilitate exchange of traffic between residential areas and flow roads, and thereby, provide access to residential areas. The Dutch name (in DVI) is "gebiedsontsluitingsweg" (literally "area access road"), the usual English term is *collector road*, i.e. a road that collects traffic from a residential area



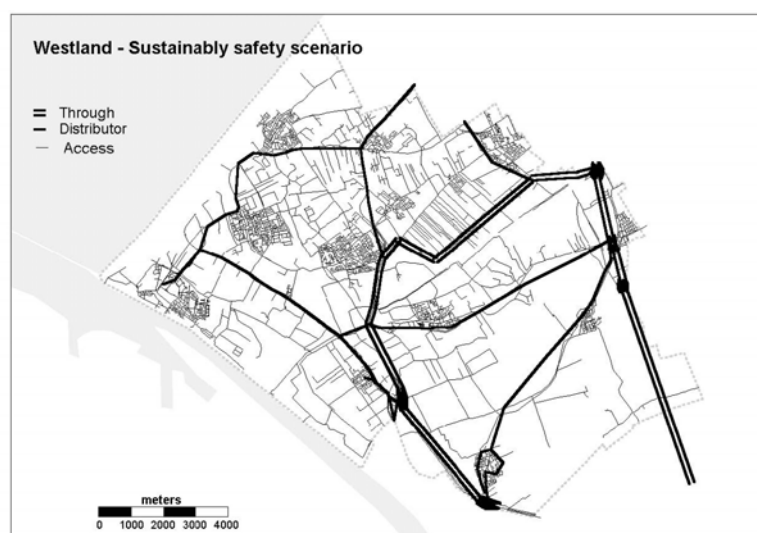
and channels the motorised traffic to flow roads. It could equally well be named *distributor road*, as it (in opposite direction) distributes motorised traffic from flow roads to local access roads. Another possible term, which is direction-neutral, would be *connection road* [Lu et al. 2003]. As collector roads and local access roads inside and outside built-up areas (also called urban environments, and extra-urban or rural environments) are considered to be different [CROW 1997], in fact, five different categories are distinguished. Flow roads are considered to be extra-urban. This standard DVI categorisation is portrayed in Figure 1.

	through road	distributor road	access road
outside the built-up area			
within the built-up area			

Note: The road depicted in the category "through road" is actually not a flow road in the strict sense as defined above, i.e. a road with separate carriageways and absence of crossing traffic, although it is intended for through traffic at higher speeds. This illustrates the limitations of the Dutch road classification, which we address by proposing a new classification (see Table 5), in which a distinction is made between (restricted access) flow roads and through roads, among other improvements.

**Figure 1** Road categories identified in The Netherlands [VMC 2004]

Figure 2 provides a real-world example of the classification of roads in an area in the Netherlands, using only the three main categories, and not the further distinction in urban and extra-urban.



**Figure 2** Road network with classification of roads: an example for an area in The Netherlands [Wegman 2003]

Table 3 provides total road length, travel distance, fatalities per 10<sup>6</sup> km and percentage of total fatalities for the five main road categories in The Netherlands for the year 1998. This table clearly demonstrates the differences per road category, and the fact that different road categories need different infrastructure measures to improve road traffic safety.

**Table 3** Road length, travel distance, fatalities per 10<sup>6</sup> km and percentage of total fatalities for the five main road categories in The Netherlands for the year 1998 [Janssen 2005]

road type	road length (km)	%	travel distance (10 <sup>6</sup> vehicle-km)	%	fatalities / 10 <sup>6</sup> km	% of total fatalities
urban access road	43,416	37	8,743	7	0.0070	6
urban distributor road	14,937	13	21,155	18	0.0146	29
rural access road	47,167	40	12,929	11	0.0236	29
rural distributor road	7,375	6	18,093	15	0.0107	18
through road	4,816	4	57,724	49	0.0034	19
total	117,711	100	118,643	100	0.0090	100

## Functional road function classification in the USA

In the USA four major categories are distinguished: interstates, arterials, collectors and local roads. And for each of these both a rural and an urban variant, making in total eight different categories [FHWA 2000a]. These are portrayed in Figure 3.

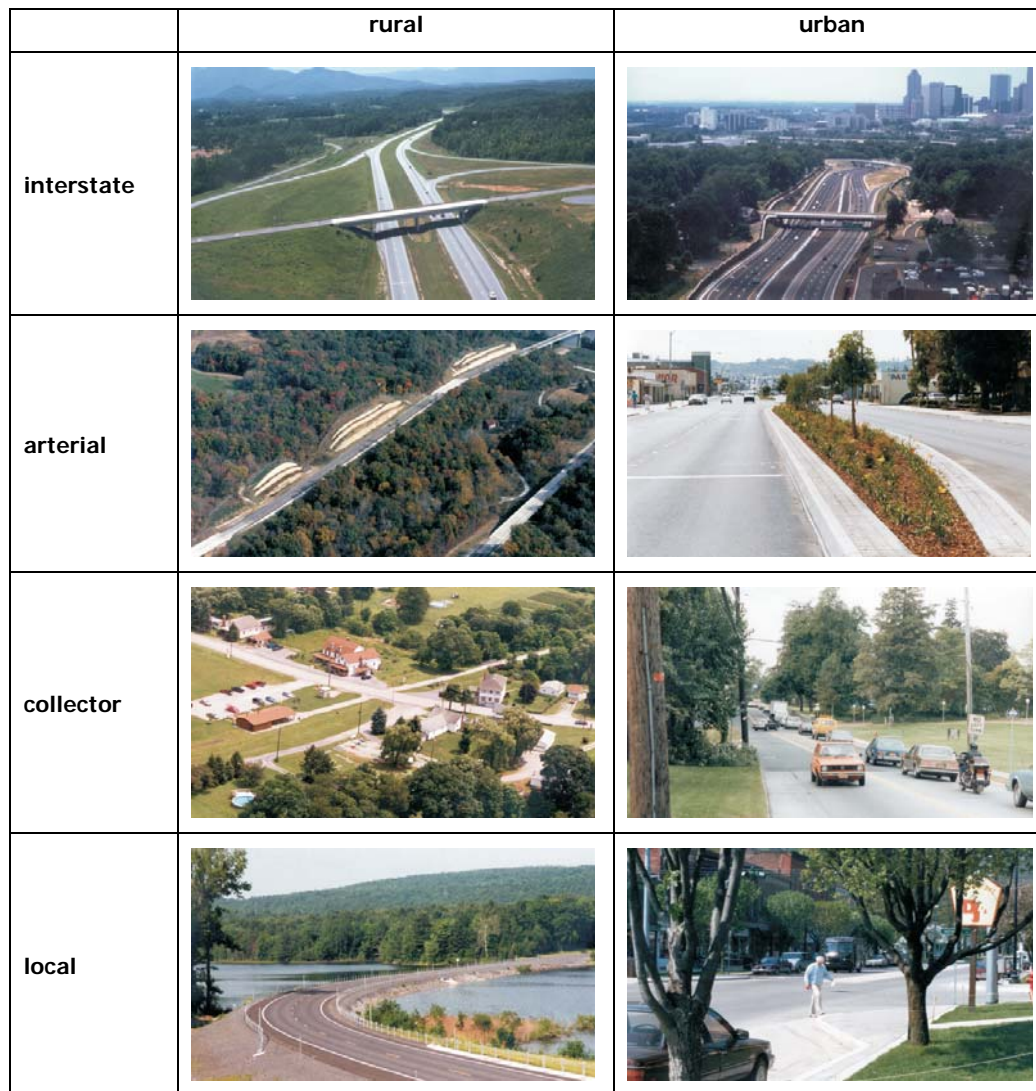
Table 4 provides total road length, travel distance, fatalities per 10<sup>6</sup> km and percentage of total fatalities for the four main road categories in the USA for the year 1999. Also this table clearly illustrates the differences per road category, and the fact that different road categories need different infrastructure measures to improve road traffic safety.

## Functional Road Class in navigable digital map databases

The providers of digital map databases for in-vehicle systems constitute another source for road categorisation. These databases were originally designed for navigation systems, but are currently evolving for use in other in-vehicle applications (driving assistance systems). They use a data model that is largely based on the GDF (Geographic Data Files) standard [CEN 1993; ISO 2004]. Road categorisation in a navigable database is an essential element for route calculation.

While both the previous two categorisations and the GDF one are functional, i.e. based on the function or purpose of the road, there is a subtle difference in the type of function that is taken as the basis. In the first two categorisations the different categories are distinguished based on the function of the road in traffic and mobility, while in GDF the categorisation is based on the importance of the role that the road performs in the connectivity of the total network, and on the connected graph principle. This means each road element (the GDF term for a database edge or link with a vehicular function) of a certain class is connected to (and thereby forms a connected graph with) all other road elements in the map database of that class, via one or more road elements of the same class or higher (i.e. more important) classes.

The attribute for road categorisation in GDF is Functional (Road) Class (FC). GDF provides ten levels for this attribute, with attribute code values 0 to 9, and semantical values "main road" (code value FC=0), "first class road" (FC=1), and so on until "ninth class road" (FC=9).



**Figure 3** Road function classifications in the USA [FHWA 2000a]

**Table 4** Road length, travel distance, fatalities per 10<sup>6</sup> vehicle-km and percentage of total fatalities for the four main road categories in the USA for the year 1999 (after [FHWA 2000a])

road type	road length (km)	%	travel distance (10 <sup>6</sup> vehicle-km)	%	fatalities / 10 <sup>6</sup> vehicle-km	% of total fatalities
local road	4,311,528	68.6	579,933	13.4	0.0132	18.7
collector	1,227,054	20.3	637,431	14.7	0.0135	21.0
arterial	624,223	9.9	2,078,101	47.9	0.0092	46.7
interstate	74,149	1.2	1,034,893	23.9	0.0054	13.6

Not all of these ten levels are used in practice, and the definition of five levels appears to be sufficient, partly because a further characterisation of a road is possible with the GDF attribute Form of Way (FW). This describes certain aspects of the physical form that a road element takes, based on a number of physical and traffic properties. It comprises coding for the semantical values "part of a motorway"; "part of a multiple carriageway which is not a motorway"; "part of a single carriageway"; "part of a roundabout circle"; "part of a slip road"; "part of a service road"; "part of a pedestrian zone"; and "part of a walkway not passable for vehicles"; amongst some other values that are less relevant here. The GDF

functional road categorisation does not distinguish between urban and rural. However, GDF allows to specify a user-defined attribute "urban" for all vehicular database links, with values yes/no, related to within or without built-up area.

The GDF functional road classification may also be considered a proper categorisation for use in simulation studies, for instance of traffic management.

## Delineation of the terms urban/extra-urban

In road categorisations roads are distinguished in either urban/extra-urban, or inside/outside the built-up area. The term rural is used as more or less synonymous to extra-urban. The terms urban/extra-urban are ambiguous, as they may be understood either as inside/outside the city, or inside/outside the built-up area. The distinction inside/outside the built-up area is the more relevant one for road categorisation. In the rural environment, outside the city, built-up areas (and roads) may exist, and these essentially have a similar character as built-up areas (and roads) in the city, even if these rural built-up areas may sometimes be very small in size. On the other hand, a rural area that is sparsely populated with houses and farms has a character that is rather different from a built-up area. This difference is reflected in the character of the roads in these two types of areas. Therefore, we propose to define the terms urban and extra-urban in the context of road categorisation as inside and outside built-up areas, and to avoid the use of the term rural, as it is ambiguous as well.

In ISO [2004] a built-up area is defined as: "An area with a concentration of buildings. In these areas, an inner city speed limit generally applies.", and further described as follows: "No exact Relationship exists between a Built-up Area and a municipality. In some cases a Built-up Area relates to exactly one municipality having the same name. However, in rural areas in particular, one municipality can contain several small Built-up Areas. Also situations exist (Paris, Brussels) in which a Built-up Area, referenced by most people by one single name, is spread over several municipalities or other kinds of Administrative Areas."

## Proposal for an improved road categorisation

In this section an alternative functional road categorisation is proposed, taking into account details of the aforementioned categorisations, the more precise delineation of the terms urban/extra-urban, and based on the following considerations:

1. The DVI categorisation provides insufficient detail, as within one category roads may exhibit considerable differences in character and layout, and thereby have different traffic safety parameters. The US classification provides a better granularity, which however, can be further improved.
2. Terminology and the hierarchy of terms is an issue. Existing terms may have slightly different use and (implicit or explicit) definition in different contexts. Identified terms in hierarchical order based on the function of the road in traffic and mobility (importance, traffic volume and typical speed; from high to low levels): flow road, through road, arterial, collector or distributor, (local) access road. We use here the following definitions:

<i>flow road</i>	through road with restricted access
<i>through road</i>	road for relatively high traffic volumes and speeds (levels may be different for urban or extra-urban environment), restricted to motor vehicles, not with restricted access
<i>arterial road</i>	road for moderate to high traffic volumes and speeds (levels may be different for urban or extra-urban environment), often with

- separation of motor vehicles and other traffic, especially in the urban environment
- collector road* road for moderate traffic volumes and speeds, and with the specific function to connect the local access roads of a built-up area to nearby arterial and through roads, sometimes with separation of motor vehicles and other traffic
- distributor road* different term for collector road; these terms are one-sided, as they only describe one direction of the traffic, and a more neutral term such as "connection road" may be used instead
- local access road* lowest level of roads, providing direct access to sojourn areas (including houses, shops and offices), generally with mixed traffic
3. A distinction can be made between extra-urban and urban flow roads. Although in The Netherlands urban flow roads are quite rare, they do actually exist (e.g. the "Utrechtsebaan" in The Hague), and in other countries they are more common.
  4. Extra-urban through roads, such as, for example, the N-roads (national roads) in The Netherlands, are distinguished as a separate category. These allow moderate speeds (80 or 100 km/h) but may have (and generally do have) level crossings with other roads.
  5. In parallel urban through roads are distinguished, with lower speed limits than extra-urban through roads. These are often continuations of, or connections between extra-urban through roads, for instance, in The Netherlands N-roads, and in Germany B-roads (Bundesstraßen), and in such cases generally carry the corresponding numbering in the urban environment.
  6. Furthermore, in the urban environment arterial roads and collector roads are distinguished, and in the extra-urban environment arterial roads, but not collector roads. A collector road is considered here as typical for a built-up (and thus urban) environment, even if it exists in a village.
  7. A useful subdivision is possible of urban local access roads into urban access roads in special low speed zones, and standard urban streets. Low speed zones are the 30 km/h zone, generally consisting of standard urban streets with a 30 km/h speed limit and infrastructure to slow down traffic, and the "woonerf" (a Dutch term used internationally for this type of zone), which is a residential area with a specific VRU (Vulnerable Road User) friendly design, equal status for all traffic modes, and a speed limit of 15 km/h (for details see Section "Composite measures: low speed urban zones"). Standard urban streets generally have a 50 km/h speed limit.
  8. As a consequence of the above delineation of the terms urban/extra-urban, extra-urban low speed local access roads are not distinguish. Woonerf and 30 km/h zones should be typified as urban.
  9. It is worthwhile mentioning that Buchanan [1964] distinguishes for the urban environment primary distributors, district distributors and local distributors, which in our definition would be named urban through roads, urban arterial roads and urban collector roads respectively.

The thus defined categories for an alternative road categorisation are summarised in Table 5. The categorisation is extended as compared to the DVI categorisation (ten instead of five categories). Even compared to the US categorisation, which provides more detail than the DVI one, the number of categories has increased by two. Specific to this new categorisation is the difference in the number of categories in urban and extra-urban. The table also includes the typical corresponding GDF FC levels as defined for digital map databases.

**Table 5** A proposed alternative road categorisation, and corresponding typical Geographic Data Files (GDF) Functional Road Class (FC) levels

<b>urban (built-up area)</b>	<b>typical speed limit (km/h)</b>	<b>GDF FC</b>	<b>extra-urban (outside built-up area)</b>	<b>typical speed limit (km/h)</b>	<b>GDF FC</b>
low speed local access road	15 / 30	4	-	-	-
local access road	50	4	local access road	50 / 60	4
collector road	50	3	-	-	-
arterial road	50 / 70	2	arterial road	70 / 80	2 / 3
through road	70	1	through road	80 / 100	1 / 2
flow road	70 / 100	0	flow road	100 / 120	0

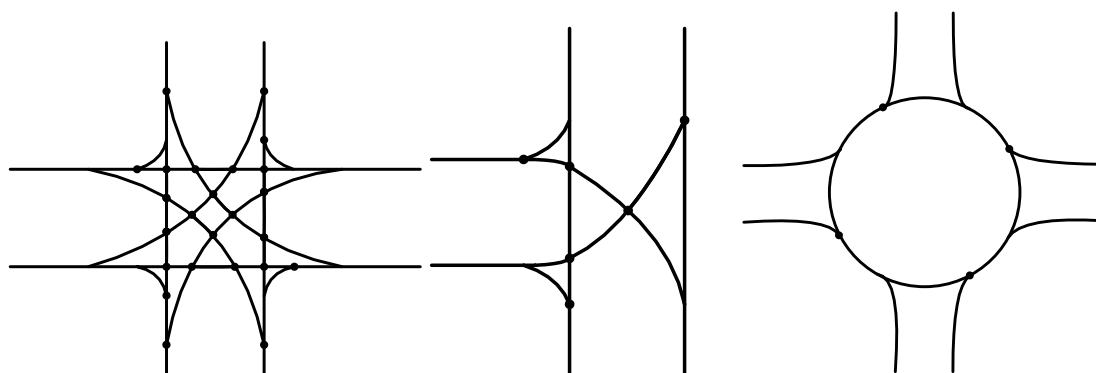
Taking into account what was stated under point 1, it may be concluded that the proposed alternative classification provides a granularity that better aligns with traffic safety requirements. However, linking with traffic safety parameters can still be improved. This needs further research, and may lead in the future, to a further improved road categorisation, primarily based on such parameters. Such categorisation may be useful to define optimal routes from a traffic safety perspective, both in traffic simulation studies on dynamic route guidance, as well as in practice in navigation systems, if introduced into in-vehicle digital maps.

## INFRASTRUCTURE MEASURES TO IMPROVE TRAFFIC SAFETY

This section provides an overview and summary description of infrastructure measures for enhancing traffic safety. In subsequent subsections groups of measures are described that specifically apply to intersections, road sections, the network as a whole, and low speed urban zones respectively. Measures in the first two groups can be typified as elementary, in contrast to the measure "low speed urban zones", which draws on many of the elementary measures, and can therefore be typified as composite. The macroscopic network layout described in the third subsection is neither an elementary nor a composite measure, but may be typified as a structural measure. This overview was composed based on literature review, e.g. [Ogden 1996; Lay 1991; CROW 2002a,b,c,d; Elvik & Vaa 2004]. Before-and-after study is the method that is mainly used for studying the impacts of infrastructure measures. Safety effects of road infrastructure measures have been exhaustively studied using meta-analysis by Elvik & Vaa [2004].

### Safety measures focusing on intersections

Main factors affecting safety at intersections are: number of legs, angle of intersection, sight distance, alignment, auxiliary lanes, channelisation, friction, turning radii, lighting, lane and shoulder widths, driveways, right of way (rules, signs, signals), and approach speed [Transportation research Board 1987]. A standard intersection with four single-carriageway connecting roads has 24 points of potential conflict (16 for crossing and 8 for merging traffic flows; see Figure 4, left diagram); and a standard T-junction has 6 such points (3 for crossing and 3 for merging traffic flows; see Figure 4, middle diagram). It should be noted that in [FHWA 2000b] diverging points are also seen as potential conflict points, which for a standard intersection with four single-carriageway connecting roads raises the number of potential conflict points by 8 to a total of 32. It is stated that the type of collision involved here is front-rear, probably due to a sudden stop of a vehicle before actually diverging. However, this is a type of situation that may occur anywhere in the network, and is not specific for an intersection.



left: four-leg crossing (24 points); middle: T-junction (6 points); right: roundabout (4 points)

**Figure 4** Potential conflict points of major conflict of intersection (adapted from [Lay 1991])

### Priority signs, traffic lights and grade separation

Uncontrolled intersections rely on a general priority rule to indicate a right of way. Some control may be applied to an intersection by giving one of the crossing roads priority over the other one, indicated by *priority signs* (right-of-way signs on the road having priority, and give-way (yield) signs or stop signs on the road not having priority). The effects of yield signs at intersections, in terms of both injury and property damage only accidents is estimated as -3%, in which the 95% confidence intervals for these types of accidents are (-9; +3) and (-12; +7) respectively [Elvik & Vaa 2004, p.497]. Stop signs may affect the number of injury accidents by -19% (-38; +7) in three-leg junctions, and by -35% (-44; -25) in four-leg junctions [Elvik & Vaa 2004, p.501]. However, Ogden [1996] reported that the stop sign may increase rear end collisions at intersections by 40-60%.

An interesting solution from a traffic safety and traffic calming point of view, which may be found in the USA, is the *n*-way application of the stop sign to each of the *n* connecting roads of a crossing (indicated by an additional *n*-way sign), with the implicit rule "first stop, first pass".

*Traffic lights* provide another means to control traffic at intersections, and are widely used as such, especially in the built-up area. They may operate with a fixed time intervals scheme, or with a more traffic demand responsive vehicle-actuated scheme. Separate intervals for all turning traffic may be especially attractive from a traffic safety perspective, but is not always applied. The best estimates for the effects of traffic signal control at T-junctions are -15% (-25; -5) for injury accidents, and -15% (-40; +15) for damage only accidents; and for the effects of traffic signal control at crossroads -30% (-35; -25) for injury accidents, and -35% (-45; -25) for damage only accidents [Elvik & Vaa 2004, p.505].

*Grade separation* at intersections is the ultimate solution, but also a costly measure and generally only applied to major roads. A grade-separated interchange instead of a T-junction may affect the number of accidents in the intersection area by +1% (-20; +28); and a grade-separated interchange instead of crossroads may largely affect accidents by -50% (-57; -46) [Elvik & Vaa 2004, p.310].

### Speed reducing structures at intersections

At a *raised intersection* the whole area of the intersection is raised (Figure 5.1). It can be viewed as an extended 3-directional or 4-directional speed hump, and has the purpose of reducing speed and raising attention. Raised intersections may affect the number of injury accidents by +5% (-34; +68), and affect the number of property damage only accidents by +13% (-55; +183) at intersections [Elvik & Vaa 2004, p.533].



Other measures at intersections include the *road stud* (Figure 5.2), the *median island* (Figure 5.3), *extended kerb* (Figure 5.4), *reduced intersection radius* (Figure 5.5), and *objects in the intersection* (figures 5.6 and 5.7).

*Speed humps* may be used on road sections in the approach to an intersection to reduce speed at the intersection. For details, see the sub-section "Speed control measures" of the Section "Safety measures focusing on road sections".



1. raised 30 km/h intersection



2. 4m spheres (road studs)



3. median narrowing



4. extended sidewalk at T-intersection



5. reduced intersection radius



6. circular object in intersection



7. rectangular object in intersection



8. roundabout in 60km-h zone



9. roundabout on extra-urban road

**Figure 5** Examples of road infrastructure measures [Schermers & Van Vliet 2001]

### Intersection channelisation

Channelisation is the use of painted road markings, raised kerbs, traffic islands or bollards to guide vehicles along a specific path on the approach to and exit from an intersection. It provides positive guidance to the driver, and as a result simplifies the movements and reduces the room for error, reduces confusion, and separates and localises the conflict points. Elvik and Vaa [2004, p.294] stated that the majority of various forms of channelisation has more favourable safety effects at crossroads than at T-junctions; at crossroads, the best estimates for the effect on injury accidents are -17% (-41; +17) for physical minor road channelisation; -4% (-25; +22) for left-turn lanes; +13% (-83; +348) for right-turn lanes; -27% (-37; -15) for physical full channelisation; and +57% (-68; -42) for painted full channelisation. According to Ogden [1996] channelisation may contribute to 20-40% accident reduction at intersections.



## Roundabout

A roundabout is a traffic control device at an intersection consisting of a one-way circulating road around a central island (figures 5.8 and 5.9). Roundabouts contribute to improving traffic safety in several ways: (1) the number of potential conflict points is reduced as for a standard intersection with four single-carriageway connecting roads the number of crossing flows is reduced to 0 and the number of merging flows to 4 (see Figure 4, right diagram); (2) with the priority rule for traffic on the roundabout, road users approaching the roundabout have to give way to road users on the roundabout (which also regulates flow); (3) speed direction differences are minimal, as all traffic inside the intersection comes from nearly the same direction, and meets at a small angle; (4) the most hazardous situation of a standard intersection, a left turn manoeuvre at which oncoming traffic is crossed, is eliminated; and (5) because of the lateral displacement the speed of the vehicle is necessarily reduced [Elvik & Vaa 2004]. It should be noted that the abovementioned view from the US of additional conflict points at diverging traffic flows leads to 4 additional such points at roundabouts [FHWA 2000b]. From conflict studies of small roundabouts in Sweden, Hydén and Vårheli [2000] draw the conclusion that these roundabouts considerably reduce traffic speed at the junctions and on the links between roundabouts, and affect the overall injury accident risk by –44%. Elvik and Vaa [2004, p.298] reported that the best estimates for the effects of converting intersections (three-leg or four-leg, yield or traffic signal before) to roundabouts are –11% (–40; +32) to –41% (–47; –34) for injury accidents, and +32% (+5; +66) to +73% (+39; +117) for property damage only accidents. Also, Elvik [2003] finds a tendency that smaller roundabouts have a lower accident rate than larger roundabouts. Ogden [1996] estimates that roundabouts may largely reduce accident rate at intersections, however may increase rear-end collisions by 0-30%. SWOV research indicated that reconstruction of an ordinary crossroads into a roundabout may decrease the total number of casualties by 75% [Dijkstra 2004].

## Separation of traffic modes

Separation of motorised traffic and bicycles at standard intersections and roundabouts, by *separate bicycle tracks*, occurs both at standard intersections and at roundabouts, when the connecting roads have separate bicycle tracks. It may also sometimes occur while the connecting roads have only bicycle lanes or no specific arrangements for bicycles at all.



1. intersection with isolated & solitary bicycle track



2. intersection with isolated bi-cycle-moped track



3. intersection with major bicycle route

**Figure 6** Examples of road infrastructure measures [Schermers & Van Vliet 2001]

See figures 6.1, 6.2 and 6.3. This measure has been commonly applied in Europe, e.g. Denmark, Sweden and The Netherlands. However, according to Danish and Dutch research [Jørgensen, E. & Jørgensen, N.O. 1994; Dijkstra 2004] roundabouts with separate bicycle tracks are not safer for cyclists than without such separate track.

## Safety measures focusing on road sections

### Separation of traffic modes

A *bicycle lane* is a small lane on each side of the road separated by a broken line. Sometimes the bicycle lane is given a different colour. It is a non-mandatory lane, which aims to reduce conflict between the cyclists (or other VRUs) and motorised traffic (which may have large differences in speed and mass). The separation is more psychological than physical, especially when the bicycle lanes are very narrow and the remaining part of the road is only about one vehicle wide, as sometimes occurs on roads of limited width, especially in the environment. If the lane is rather narrow and not indicated with a bicycle drawing in the lane, it is called a *bicycle suggestion lane*.

A *bicycle track* is a special path for bicycles, which is physically separated from the main road. It provides a better solution (complete separation of traffic types with considerable differences in speed) but requires more space. According to research in Norway [Elvik & Vaa 2004, p.273], tracks for walking and cycling do not reduce accidents, on the contrary, they increase the number of injury accidents.

A *service road* is comparable to a bicycle track, but is also accessible to slow motorised traffic (which means that the separation is not complete), and requires even more space.

### Separation of opposing traffic flows on single-carriageway extra-urban roads

Single-carriageway extra-urban through roads are notoriously hazardous. The speed differences may be high (e.g. up to 200 km/h at a 100 km/h speed limit, or even higher when the speed limit is not obeyed, especially at overtaking manoeuvres), lanes are close, and overtaking is common.

The simplest measure is *overtaking prohibition*, marked with signs and a single or, more compelling, double white line.

To make the double white line even more compulsory, sometimes extra space is created for a *central reservation* or *median* (see Figure 7.4) between the two white lines (lane separation by space). For an increased effect, this central reservation may even use a different colour to draw the attention of the driver (see, e.g. Figure 1).

A next step is to build a *passable structure at the central reservation*, either as a kind of hump or as a dip (lane separation by a non-blocking structure). It is obvious that such structures may be dangerous at higher speeds.

The ultimate solution is *physical lane separation* for opposite directions. This may, for new roads, be done by creating a sufficiently wide and non-passable central reservation (which then basically converts a two-lane bidirectional carriageway into two single-lane one-way carriageways). In Sweden, on existing single-carriageway roads, a middle steel wire barrier is sometimes implemented, to create the same effect. This is a rigorous implementation of the aforementioned speed rule "never have opposite traffic without separation at speeds higher than 70 km/h" (see Section "Concept of road traffic safety").

As part of the risk originates from overtaking, another solution, if sufficient space is available, is a so-called *2+1 carriageway* [TranScan 2001]. This involves creating a three-lane single-carriageway, where each direction has alternately, e.g. every 3 km, the availability of 2 lanes, to allow overtaking. The two directions are generally only separated by lane markings, but sometimes, especially in Sweden, by steel wire barrier.

The effect of overtaking lanes (passing lane on one direction) on the number of injury accidents is –18% (–27; –8), and on the number of property damage only accidents –20%

(-26; -13) [Elvik & Vaa 2004, p.324]. On two-lane roads in extra-urban areas, to construct central reservations affects the number of accidents by +94% (+41; +165) for injury accidents, and by +128% (+75; +197) for property damage only accidents; on two-lane roads in urban areas, medians are associated with an effect on the number of accidents of +39% (-49; -27); concerning the effects of medians on multi-lane roads in extra-urban areas, injury accidents and property damage only accidents are affected by -12% (-15; -8) and -18% (-21; -14) respectively; for medians on multi-lane roads in urban areas injury accidents are affected by -22% (-24; -20), while property damage only accidents are affected by +9% (+7; +11) [Elvik & Vaa 2004, p.327].

### Measures to prevent single vehicle run-off road

Measures to prevent collisions of vehicles with roadside objects are collectively addressed as roadside safety measures. These include two basic items: measures to prevent or correct a single vehicle run-off road incident (discussed in this subsection), and measures to prevent or mitigate collisions with roadside obstacles once a single vehicle run-off road incident cannot anymore be avoided (discussed in the next subsection).

Measures prevent or correct a single vehicle run-off road incident comprise treatments to warn the driver and induce corrective action at imminent run-off road situations. The basic measure is clear *lane markings* in the form of a white line along the road.

*Rumble strips* are road edge lines that have small ridges or grooves in lateral direction, and may be integrated in lane markings made of adhesive tape (ridges) or milled into the road surface (grooves, generally just outside the lane marking). They give a rumbling sound when driven over and so alert the driver to take corrective action.

A *recovery area* is a zone beside the road within which the driver is likely to be able to regain control of the vehicle if it has not struck a fixed roadside object or rolled over. The area design depends upon the speeds at which vehicles may be travelling on a particular road, and the road layout.

A *hard shoulder* (of the same surface material as the road) or *semi-hard shoulder* (of a surface material softer than the road, but harder than the surface outside the road) helps to keep control of the vehicle even if it has slightly gone out of its lane. A hard shoulder is preferred on higher speed through roads, while a semi-hard shoulder may be used on extra-urban arterial roads.

### Measures to prevent collisions with obstacles along the road

Two types of situations are relevant. The first relates especially to the built-up area, and concerns the presence of parked vehicles along the road, which may cause conflicts with moving vehicles on the road, but also with bicycles and mopeds. This problem can be addressed by regulation (prohibition to park along the road) or by adaptation of road layout. Chokers (a speed control measure, see the section below) may help to prevent conflicts between moving and parked vehicles (see figures 8.1, 8.2 and 8.3), but at the same time introduce new obstacles along the road.

The second situation relates mostly to extra-urban roads, and concerns potential collisions when a single vehicle leaves the road in a single vehicle run-off road incident, and strikes a roadside object.

A typical roadside safety measure to prevent or mitigate collisions is the creation of an *obstacle-free zone* (also called *roadside clear zone*). This is an area alongside the road that is kept free of fixed obstacles like trees, lampposts, gantry and traffic sign supports, and permanent structures of overpasses. *Crash barriers* (e.g. guard rails) may be applied at places where clearance of fixed obstacles is not possible. In addition they may be used at

places where the roadside slopes down. Flattening such road side slopes may also help to improve traffic safety. At places with a risk of a vehicle having a frontal encounter with a roadside object, e.g. at bifurcations, *impact attenuators* or *crash cushions* may be used, which are able to absorb a certain amount of kinetic energy from the vehicle before it hits the object.

Effects on accidents of new guardrails along the roadside [Elvik & Vaa 2004, p.350] are –44% (–54; –32) for fatalities, –47% (–52; –41) for injuries, and –7% (–35; +33) for total accidents. Flattening side slopes reduces both the number and severity of accidents: flattening slopes from 1:3 to 1:4 affects injury accidents by –42% (–46; –38), and property damage only accidents by –29% (–33; –25); flattening slopes from 1:4 to 1:6 affects injury accidents by –22% (–26; –18), and property damage only accidents by –24% (–26; –21) [Elvik & Vaa 2004, p.332]. Effects of increased distance from roadside obstacles vary from –22% (–46; –43) (for 1 to 5 metres) to –44% (–24; –20) (for 5 to 9 metres) [Elvik & Vaa 2004, p.333]. Effects of crash cushions for fatality accidents are –69% (–83; –46), for injury accidents –69% (–75; –62), and for property damage only accidents –46% (–63; –23) [Elvik & Vaa 2004, p.353].

### Speed control measures

As excessive speed is an important cause of accidents involving motor vehicles, and an important determinant of the gravity of such accidents [Taylor et al. 2000; Treat 1980], speed control measures are relevant instruments to improve traffic safety, especially in urban situations with mixed traffic including VRUs. The basic measure for speed control is to establish a speed limit. Infrastructure based speed control measures may be used to enforce adherence with such speed limits. These apply especially to 50 km/h and 30 km/h zones. Two main categories of infrastructure based speed control measures can be distinguished, elevated structures and road narrowing.



1. 30 km/h speed hump



2. raised pedestrian crossing



3. 30 km/h plateau



4. median and lane narrowing



5. bus-friendly speed cushion



6. 30 km/h speed cushion

**Figure 7** Examples of road infrastructure measures [Schermer & Van Vliet 2001]

Elevated speed reduction structures are related to the raised intersection. In general, they consist of elevations of the road surface that force the driver to slow down to a certain speed. The most well known are the (sinusoidal) *speed (control) hump* (Figure 7.1) and the (trapezoidal) *speed (control) elevation*. The latter often serves as a *raised pedestrian*



*crossing* (Figure 7.2). Speed humps may affect the number of accidents by –48% (–54; –42) on roads with humps, and by –6% (–9; –2) on surrounding roads [Elvik & Vaa 2004, p.533]. The speed hump is named in The Netherlands "plateau" if it has a considerable length (Figure 7.3), typically more than 10 m. Other variants include *speed cushions* (figures 7.5 and 7.6).

Note that an inappropriate design may be counter-effective. In Mexico, a country well-known for its abundance of speed humps (called *topes*), also speed dips are sometimes used. This is shaped like an inverted speed hump, and constitutes a transverse hollow in the road, with the same purpose to slow down traffic. It is reported to be quite dangerous at times of severe rain and flooding, having caused even fatal accidents. Also the *tope* may have adverse effects. It has often a rather car-unfriendly design (too high and too sharp angle), and it is also extensively applied on through roads, and often poorly indicated, which makes driving in the dark a hazardous adventure.

Road (and lane) narrowing structures include *chokers* (figures 8.1, 8.2 and 8.3), *central medians* (Figure 7.4) and *chicanes* (figures 8.4, 8.5 and 8.6). The latter not only narrows the road but deflects it laterally also, which further reduces speed. In the Dutch village of Amerongen it is reported that a chicane caused several single vehicle run-off road accidents after it was installed, which is another indication that certain measures may sometimes have adverse effects because of an improper design or location, despite good intentions.



1. one-sided choker



2. two-sided choker



3. extended choker with one way treatment



4. 50 km/h chicane



5. 30 km-h chicane



6. 30 km-h chicane

**Figure 8** Examples of road infrastructure measures [Schermers & Van Vliet 2001]

## Generic safety measures for the whole network

### Network layout

In contrast to the micro-layout of the network, which involves the local application of many of the structural elements described above, the macro-layout of the network concerns the layout of the network as a whole in a certain area (e.g. village, neighbourhood, city or province), and is related to spatial planning. Some of the DVI traffic safety requirements point to this macro-layout. Especially large-scale modifications in the macro-layout are sometimes rather theoretical, as these involve the complete infrastructure of network,

buildings and unbuilt areas, and are thereby often largely impossible and generally not cost-effective. However, two measures at a smaller scale may be safety-effective and cost-effective: (1) the implementation of changes in connectivity in sojourn areas, by cancelling or blocking certain connections, in order to reduce or eliminate through traffic, thereby improving the sojourn function of the area; (2) the creation of bypasses around villages and smaller cities for roads that historically lead right through the village or city, to reduce through traffic. For this category of generic safety measures no data on effects are available.

### Other generic measures

There are several other generic measures that apply to the whole network. These include *road lighting*, *lane marking*, *regulatory road signs*, *warning road signs* and *information road signs*. These measures are quite standard elements of proper road design, yet improvements thereof may sometimes contribute to traffic safety.

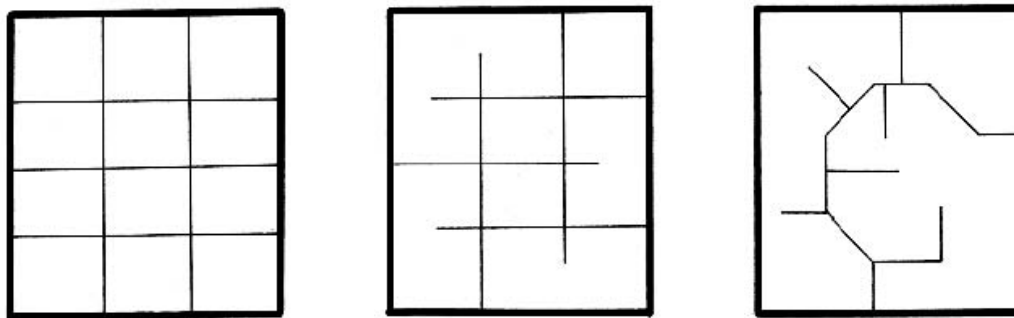
Of the regulatory road signs, the speed limit signs are especially important for traffic safety, as the chance and effect of traffic accidents bear a relationship with speed. However, setting the speed limit is one thing, to enforce conformance is another. Several of the abovementioned measures have the effect of slowing down traffic and enforcing the speed to be more or less conformant with the local speed limit.

Elvik and Vaa [2004, p.367] state that the effect of improved road lighting on the number of accidents depends on the level to which the lighting is increased: an increase to double the previous lighting level affects injury accidents by –8% (–20; +6) and property damage only accidents by –1% (–4; +3); an increase to 2 to 5 times the previous level of lighting affects injury accidents by –13% (–17; –9) and property damage only accidents by –9% (–14; –4); an increase to 5 times the previous level of lighting or above, affects fatal accidents by –50% (–79; +15), injury accidents by –32% (–39; –25), and property damage only accidents by –47% (–62; –25).

### Composite measures: low speed urban zones

Two types of low speed urban zones may be distinguished: *30 km/h zones* and *woonerf zones*. In the Dutch term "woonerf", the element "woon" specifically refers to a residential area (like the English term "home zone"). For that reason, in Dutch regulation the term "woonerf" has in the mean time been replaced by "erf", to give it a wider applicability to all types of sojourn areas, including e.g. areas for shopping, offices and recreation." However, as the term "woonerf" has become internationally adopted for this type of zone, it may still be used. Implementing such zones is a composite measure employing several of the abovementioned elementary measures. It encompasses an integrated treatment of all or a certain part of the roads in a (residential) area, by establishing an overall 30 km/h speed limit (30 km/h zone) or at walk speed limit (woonerf zone; the at walk speed limit is generally interpreted as 15 km/h), and by implementation of various kinds of speed-reducing treatments (both in terms of infrastructural elements and of road layout as mentioned above), to enforce this speed limit. In addition, the woonerf zone has a specific layout that treats all traffic modes equally. Generally the woonerf zone involves intensive implementation of elementary measures with a high level of integration, while the 30 km/h zone exhibits a modest implementation of such measures. The composite zone measures are especially intended to protect VRUs in a mixed traffic situation. The most common structural elements applied in these zones include speed humps and cushions, chokers, central medians, traffic islands, and chicanes for road sections, and raised junctions, road studs, extended kerbs, objects on the road and separate bicycle tracks for intersections [Schermers & Van Vliet 2001].

Figure 9 illustrates the three main network layout structures for residential areas: the classical grid network layout; the limited access grid network layout; and the organic network layout, which also has limited access [Dijkstra 1997]. The organic layout corresponds to the "Radburn scheme" discussed by Buchanan [1964]. All three layouts allow the creation of 30 km/h zones while the two limited access network layouts, and especially the organic one, are most adequate to create a woonerf zone, where the enforcement is strengthened by the limited access to the area, and the completely equal treatment of pedestrians, bicycles and motorised traffic: the sidewalks that are present in a standard residential area, are omitted. In general the woonerf zone is thought to improve the living environment, and it has been shown that the number of accidents drops [OECD 1990; Vis & Dijkstra 1992]. However, besides spatial and financial problems it has appeared that inhabitants miss these separate pedestrian provisions, and for this reason the concept is considered to be less suitable for larger, continuous built-up areas [Vis 1997, p27]. A 30 km/h zone may affect injury accidents by -27% (-30; 24), and property damage only accidents by -16% (-19; -12) [Elvik & Vaa 2004, p.533].



left: classical grid network structure; middle: limited access grid network structure; right: organic network structure

**Figure 9** The three main residential area network structures [Dijkstra 1997]

A concept similar to 30 km/h zones is *traffic calming*. It is defined by MASTER Consortium [1998] in the following way: "Integrated treatment of areas or stretches of road with various kinds of speed-reducing measures in urban areas; frequently combined with other measures like road closures, one-way streets and reorganisation of road hierarchy."

## DISCUSSION AND CONCLUSION

The main contribution of this paper to understanding in transportation science lies in compiling a set of general traffic safety principles. Based on a review of the underlying concepts of road design focusing on sustainable traffic safety, we defined an extended set of five traffic safety principles, and sixteen more operational sub-principles or traffic safety requirements. These principles and requirements better cover the whole spectrum of traffic safety measures than previous sets, which more specifically relate to infrastructure measures, and especially provide a good basis for a functional comparative analysis of measures based on infrastructure and driving assistances systems, which is an item for further research.

Another contribution of this paper is a proposal for an alternative road categorisation. Road categorisation is an essential element in safety focused road design, as well as for an optimal selection of safe routes through the network. Based on a review of three different existing road categorisations we propose an alternative solution that better accommodates the requirements of traffic safety, and may especially be useful in further research concerning route selection (e.g. in simulation studies) with the aim of minimising traffic risk.

A systematic overview and description of relevant physical infrastructure measures and their effects is presented: elementary measures (specific and generic), composite measures and (generic) network layout. Road redesign using these measures can improve road traffic safety by either influencing velocity (i.e. speed and direction) or preventing conflict. On access roads, speed control seems more important, while on collector, arterial and through roads, direction and conflict control seem to be the key issues, although speed certainly plays its role here as well. The highest level roads, flow roads, have a design that is by nature already largely compliant with road safety principles, and therefore, traffic safety on these roads can hardly be improved by further infrastructure redesign. It should be emphasised that road redesign based on these measures may sometimes also have adverse effects, despite good intentions.

The overview of infrastructure measures provides a good basis for a comparative analysis to estimate the effects of measures for which few data and limited experience exist (see e.g. [Lu 2006]). However, the values of the traffic safety effects based on the 95% confidence interval indicate large uncertainties in the available statistical data. More reliable and representative data are required, but difficult to be obtained from statistical analysis using historical data. Safety effects of physical infrastructure measures are studied mainly at the local level (i.e. a road section or an intersection), and based on before-and-after study. Such effects are influenced by various parameters. Further research could study the possibility to develop an alternative objective method for assessing accident probability, which is not based on historical statistics, but on road function categorisation and quantitative road parameters, such as, for instance, road geometry and layout (including variables like road surface, slope and banking), flow density, legal speed limit and behaviour.

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