Motorways 2018

Transport

CONTENTS

1 Overview

What is a motorway?

A motorway is a road, specially designed and built for motor traffic, which does not serve properties bordering on it, and which: a) is provided, except at special points or temporarily, with separate carriageways for traffic in two directions, separated from each other, either by a dividing strip not intended for traffic, or exceptionally by other means; b) has no crossings at the same level with any road, railway or tramway track, or footpath; c) is especially sign-posted as a motorway and is reserved for specific categories of road motor vehicles.

Motorway design principles

Although motorway design requirements differ among countries, there are several design principles that are more or less similar in EU countries and internationally, and distinguish motorways from other road types. These include:

- A typical design speed in the range of 100-130Km/h.
- Minimum values for horizontal curve radii around 750m to 900m.
- Maximum longitudinal gradients typically not exceeding 4% to 5%.
- Cross sections incorporating a minimum of two through-traffic lanes for each direction of travel, with a typical width of 3,50m to 3,75m each, separated by a central median.
- An obstacle free zone varying from 4,5m to 10m, or alternatively installation of appropriate vehicle restraint systems.
- Proper design of grade - separated interchanges to provide for the movement of traffic between two or more roadways on different levels.
- More frequent (compared to other road types) construction of tunnels, requiring complex equipment and methods of operation.
- Installation of highly efficient road equipment and traffic control devices.

Safety benefits of motorways

Motorways exhibit much lower accident rates (injury accidents per million vehicle kilometres) than other road types. Studies comparing motorways to standard rural and urban roads indicate 50% to 90% lower accident rates for motorways. Before and after studies indicate that when a new motorway is constructed, the resulting reduction in the number of accidents is not that large: an average decrease in the number of injury accidents of around 7% has been identified. This can be justified considering firstly, that not all traffic using the existing roads transfers to the new motorway, and secondly that the construction of a motorway often generates new traffic.

Specific motorway characteristics also exhibit important road safety benefits: Central medians (with or without barriers) have been found to reduce accident rates in most situations, however, the relevant study results are not consistent. As a general observation, medians affect the distribution of accidents by type: reduced numbers of head-on collisions have been reported, but often increased numbers of less severe accidents can also be expected. Replacing at-grade intersections with grade separated interchanges is related to a reduction in the number of accidents in the range of -15% to -57%. Finally, access restriction on motorways is also related to reduced accident rates.

Motorway accidents

Although motorways exhibit reduced accident rates compared to other road types, accidents still occur, and, due to high vehicle speeds, these accidents tend to be more severe. Three types of accidents on motorways are of particular interest: (a) accidents caused by the improper use of emergency lanes, (b) cross-median head-on accidents, and (c) accidents involving driving on the wrong direction.

An investigation of accidents involving vehicles using the emergency lane in the UK came to the conclusion that the severity of these accidents was three times higher than the severity of other accidents on motorways. Respective countermeasures include the installation of rumble strips, the widening of emergency lanes, information campaigns on the use of emergency lanes on motorways, and installation of lighting.

Head-on cross-median accidents typically occur when a vehicle crosses the median and crashes with a vehicle travelling in the opposite direction, and they are usually very severe in nature. In order to reduce cross-median fatalities, engineering, enforcement and education measures are proposed with the following objectives: (1) to keep vehicles from departing the travelled way, (2) to minimize the likelihood of head-on accidents with an oncoming vehicle, (3) to reduce the severity of median-barrier accidents that occur, (4) to enhance enforcement and awareness of traffic regulations, and (5) to improve coordination of agency safety initiatives.

Wrong way accidents are caused by drivers travelling on the wrong direction on the motorway. The causes of wrong-way driving vary from inattention and unintentional error (mostly from senior drivers) to driving under the influence of alcohol or drugs and committing intentional offences in order to correct a previous mistake, e.g. missing an exit road (mostly from young drivers). Common countermeasures for wrong-way driving include engineering (signage, pavement marking, roadway geometry, and ITS), education (training), and enforcement (emergency response, confinement, and radio messages).

Managed (urban) motorways

The future of motorways is possibly related to actively managed motorways, i.e. urban motorways that have intelligent information, communications and control systems (ITS tools) incorporated in and alongside the road. These include coordinated on-ramp signalling, variable speed limits, lane control, incident detection and traffic flow data, traveller information and closed circuit television surveillance. A further typical characteristic of managed motorways is hard shoulder running. Managed motorways increase journey reliability and throughput of a motorway through speed management and increase capacity by shoulder running.

2 Definition

A motorway can be briefly described as a type of road that accommodates high-speed vehicular traffic, with divided directions of travel and controlled access for traffic at selected locations only. Other terms that are frequently used instead of motorway are: freeway, expressway and controlled access highway. Motorways are typically designed with high standards, usually have wide lanes and hard shoulders, are often equipped with road lighting, especially at interchanges, and are maintained according to high standards.

A more detailed definition according to the Vienna Convention on Road Signs and Signals (UNECE, 1968) and adopted by the European Commission (European Commission, 2003) and the UN Economic Commission for Europe (EUROSTAT - ITF - UNECE, 2009) is the following:

"Road, specially designed and built for motor traffic, which does not serve properties bordering on it, and which:
a) is provided, except at special points or temporarily, with separate carriageways for traffic in two directions, separated from each other, either by a dividing strip not intended for traffic, or exceptionally by other means;
b) has no crossings at the same level with any road, railway or tramway track, or footpath;
c) is especially sign-posted as a motorway and is reserved for specific categories of road motor vehicles.
Entry and exit lanes of motorways are included irrespective of the location of the sign-posts. Urban motorways are also included."

Many European countries use the above motorway definition; however, different national definitions of motorways can be found in different countries (see Box 1).

Box 1: Different national definitions of "Motorway"

Germany: Roads with two directions of travel and more than one lane that serve only high speed vehicular traffic (FGSV, 2008).

USA: A multilane, divided highway with a minimum of two lanes for the exclusive use of traffic in each direction and full control of access without traffic interruption (AASHTO, 2010).

Australia: A divided highway for through traffic with no access for traffic between interchanges and with grade separation at some interchanges. Certain activities or uses may be restricted or prohibited by legislative provision (Austroads, 2015a).

Regardless of the exact definition, the basic characteristics that distinguish motorways from other road types are more or less common:

- Motorways serve exclusively motorised traffic.
- Motorways have separate carriageways for the two directions of traffic.
- Motorways are not crossed at the same level by other roads, footpaths, railways etc. Traffic entrance and exit is performed at interchanges only.
- Motorways have no access for traffic between interchanges and do not provide access to adjacent land.

- Motorways are especially sign-posted.

In countries that follow the Vienna Convention on Road Signs and Signals (UNECE, 1968) motorways are sign-posted as in Figure 1 (dimensions and layout vary between countries), and the motorway qualification implies they are forbidden for walking or parking, and reserved for the use of motorized vehicles only.

Figure 1: Motorway signs

Regarding road function (see also ERSO Traffic Safety Synthesis on Roads), motorways serve exclusively the function of flow (Wegman & Aarts, 2005). They allow for efficient throughput of, usually long distance, motorized traffic, with unhindered flow of traffic, no traffic signals, at-grade intersections or property access and elimination of conflicts with other directions of traffic, thus, dramatically improving both safety and capacity.

Speed limits on motorways in IRTAD countries (OECD/ITF, 2015) vary from 90Km/h to 140Km/h, with the exception of Germany, where there is only a recommended limit of 130Km/h (see Table 1).

Table 1: Speed limits on motorways

Country	Speed Limit	Country	Speed Limit	Country	Speed Limit
Argentina	130Km/h	Hungary	130Km/h	Nigeria	100Km/h
Australia	110Km/h	Ireland	120Km/h	Norway	90-110Km/h
Austria	130Km/h	Israel	110Km/h	Poland	140Km/h
Belgium	120Km/h	Italy	130Km/h (110Km/h in wet conditions)	Portugal	120Km/h
Canada	100-110Km/h	Japan	100Km/h	Serbia	120Km/h
Chile	120Km/h	Korea	100-110Km/h	Slovenia	130Km/h
Czech Republic	130Km/h	Lithuania	120-130Km/h (110Km/h in winter)	Spain	120Km/h
Denmark	110-130Km/h	Luxembourg	130Km/h (110Km/h in wet conditions)	Sweden	110-120Km/h
Finland	100-120Km/h	Malaysia	110Km/h	Switzerland	120Km/h
France	130Km/h (110Km/h in wet conditions)	Morocco	120Km/h	United Kingdom	70mph (113Km/h)
Germany	no limit	Netherlands	130Km/h	United States	55-80mph (88-129Km/h) set by each state
Greece	130Km/h	New Zealand	100Km/h		

Source: OECD/ITF, 2015

3 Motorway network in Europe

During the last decades, many European countries, in order to improve their road infrastructure, have invested in the construction of motorways and/or the upgrade of existing roads to motorways. The total length of motorways in EU-28 at the end of 2015 has been estimated at 75.820Km (European Commission, 2017a). A detailed presentation of the size and growth of the European network of motorways since 1990 is presented in Table 2.

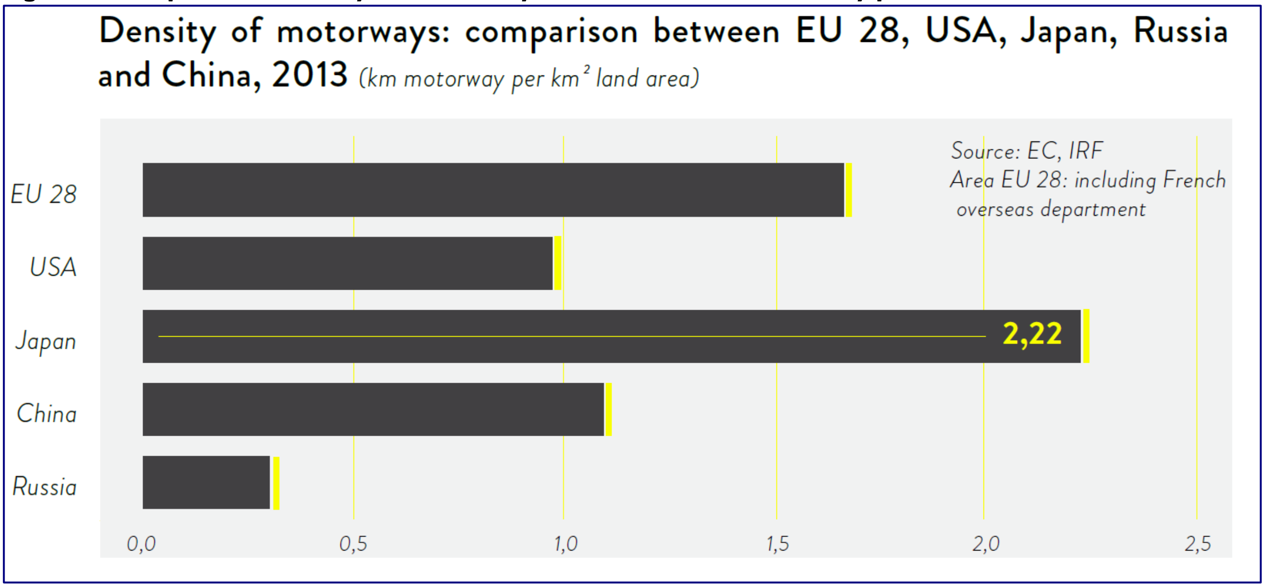
Table 2: Length of motorways in Europe (km)

	1990	1995	2000	2005	2010	2015
EU-28	42.207	48.297	55.116	63.140	71.092	75.820
EU-15	39.647	45.493	51.476	57.901	64.143	66.816
EU-13	2.560	2.804	3.640	5.239	6.949	8.974
BE	1.666	1.666	1.702	1.747	1.763	1.763
BG	273	277	319	331	437	734
CZ	357	414	501	564	734	776
DK	611	796	923	1.032	1.130	1.237
DE	10.854	11.190	11.712	12.363	12.819	12.993
EE	41	65	93	99	115	147
IE	26	70	103	247	900	916
EL	190	421	615	917	1.558	1.589
ES	4.976	6.962	9.049	11.432	14.262	15.336
FR	6.824	8.275	9.766	10.798	11.392	11.599
HR	291	302	411	1.016	1.244	1.310
IT	6.193	6.435	6.478	6.542	6.668	6.943
CY	120	167	257	276	257	272
LV	-	-	-	-	-	-
LT	421	.394	417	417	309	309
LU	78	123	114	147	152	131
HU	267	335	448	859	1.477	1.884
MT	-	-	-	-	-	-
NL	2.092	2.208	2.265	2.600	2.651	2.756
AT	1.445	1.596	1.633	1.677	1.719	1.719
PL	257	246	358	552	857	1.559
PT	316	687	1482	2.341	2.737	3.065
RO	113	113	113	228	332	747
SI	228	293	427	569	771	773
SK	192	198	296	328	416	463
FI	225	394	549	693	779	881
SE	939	1.262	1.499	1.700	1.927	2.119
UK	3.212	3.408	3.586	3.665	3.686	3.769

Source: European Commission, 2017a

In Figure 2, the density of motorways (Km of motorway per 100Km^2 of land area) is presented comparatively for EU-28, USA, Japan, Russia and China (2013 data).

Figure 2: Comparative density of motorways in 2013 (Km of motorway per 100Km² of land area)



Source: ERF, 2017

4 Motorway design principles

European countries have developed road design guidelines independently from each other; therefore, the design guidelines for motorways also differ among EU countries. There are however, several design principles that are more or less similar in EU countries and internationally, and distinguish motorways from other road types (AASHTO, 2011; DHV, 2005; FGSV, 2008).

4.1 Design speed and alignment

Motorways are generally designed for high volume and high speed operation; therefore, they are characterized by smooth horizontal and vertical alignment. Minimum radii of horizontal and vertical curves are usually calculated assuming a design speed of 80 to 130Km/h. Specifically:

- A design speed of 120Km/h is normally used in the Netherlands for Type I motorways (DHV, 2005).
- Design speeds of 120Km/h to 130Km/h are typically used in Germany (FGSV, 2008) for EKA 1 A and EKA 1 B rural motorways respectively, and 80Km/h for EKA 3 urban motorways.
- Design speeds of 100Km/h to 130Km/h are typically used in Greece.
- Design speed of 110Km/h is normally assumed for rural freeways in the US (AASHTO, 2014), reduced to 80-100Km/h for mountainous terrain.

Typical minimum values for horizontal curve radii are around 750m to 900m, in accordance to the assumed design speed and differences among countries, and longitudinal gradients typically do not exceed 4% to 5%. Sight distance requirements also necessitate long and smooth vertical curves, with minimum values for vertical curve radii around 10.000m to 13.000m for crest curves and 6.000m to 9.000m for sag curves.

4.2 Cross-sections

The basic issues to be considered for the dimensioning of motorways' cross sections are the following (FGSV, 2008):

- Traffic safety;
- Traffic flow and level of service;
- Requirements for construction, operation and maintenance of the motorway.

Normally, typical cross sections are defined based on the predicted traffic volumes and the required level of service. Furthermore, the consistency between cross sections in different but successive sections of the motorway should be considered, in order to achieve uniformity in the design and to ensure that transition sections are safe and properly understood by drivers.

For urban motorways, a further consideration is the adaptation of the cross section and the project in general with the surrounding urban environment, taking into account roadside growth, motorway level compared to the city level, construction cost and type of sound barriers (FGSV, 2008).

Normally, motorways have a minimum of two through-traffic lanes for each direction of travel, with a typical width of 3,50m to 3,75m each. A central median serves to separate opposite directions of travel and also allows for the installation of suitable road equipment, such as safety barriers, sign bridge posts, lighting posts, traffic signs, drainage systems, anti-glare equipment, etc. Paved shoulders and emergency lanes should be continuous on the side of motorway facilities.

4.3 Roadside

Roadside hazards pose a major risk to the occupants of vehicles which run off the road. Especially on motorways, where vehicle speed is high, accidents that involve running into roadside hazards tend to be more severe. In 80 km/h speed limits, 1 in 25 recorded run-off-road casualty accidents will be fatal. In 110 km/h speed limits, 1 in 15 will result in a fatality (Austroads, 2015b).

In reducing the number of single vehicle run-off-road accidents, the following objectives can be identified (DHV, 2005):

- preventing drivers running off the road;
- when a driver runs off the road, minimise the risk of accident;
- in case of an impact, reduce the severity of the accident.

In order to improve roadside safety, the most desirable alternative is a shoulder without obstacles (and without vehicle restraint system). A shoulder with safe slopes and a shoulder with fixed objects that yield easily upon collision (i.e. passively safe equipment) are also good solutions. If these solutions are not feasible, an effectively functioning vehicle restraint system (safety barrier) is the only remaining alternative (SWOV, 2002; DHV, 2005; Austroads, 2014a; Austroads, 2015b).

According to the design standards of various European countries, the width of obstacle free zone on motorways varies from 4.5m to more than 10m (SWOV, 2002). DHV (2005) suggests that at a speed of approximately 100 km/h, 80% to 90% of vehicles that run off road penetrate the shoulder no further than approximately 10m.

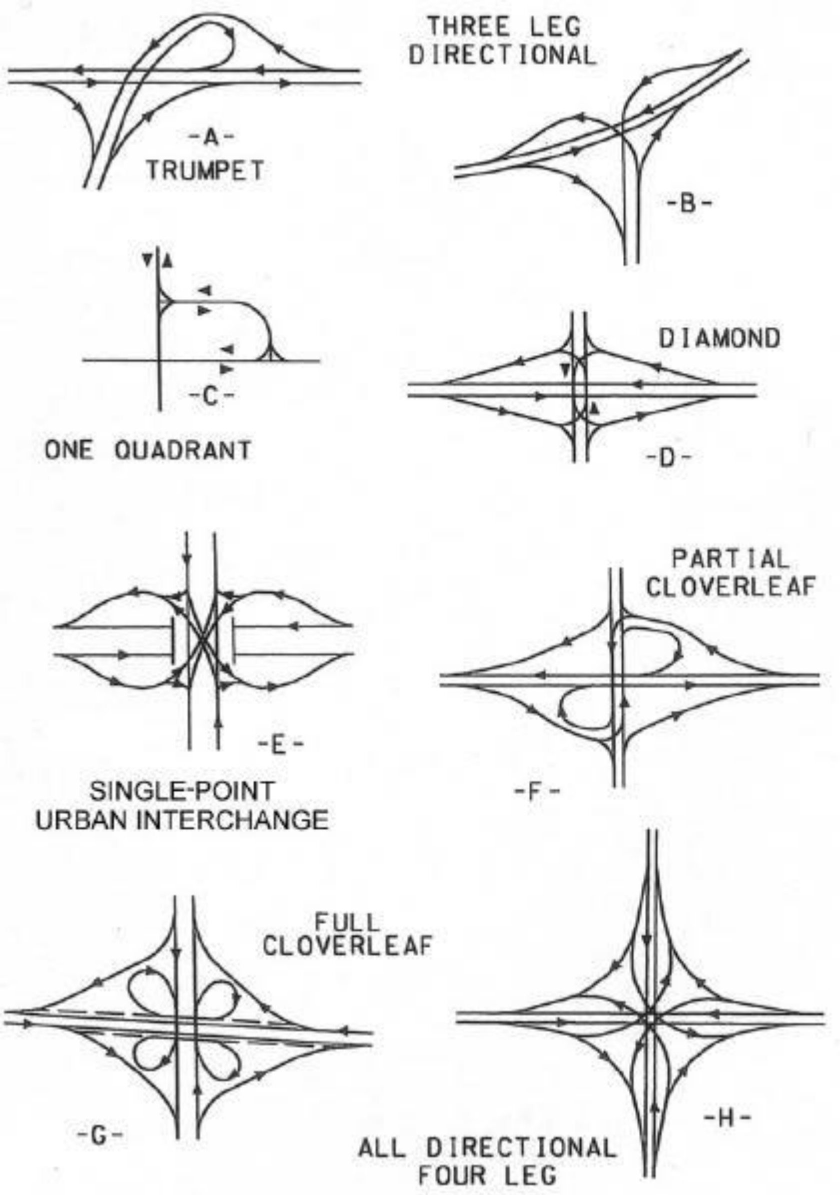
Vehicle restraint systems for motorways are further presented in Section 4.6 of this report.

4.4 Interchanges

The ability to accommodate high volumes of traffic safely and efficiently depends largely on the arrangements provided for handling intersecting traffic (AASHTO, 2011). The greatest efficiency, safety, and capacity are attained when the intersecting travelled ways are grade separated. An interchange is a system of interconnecting roadways in conjunction with one or more grade separations that provides for the movement of traffic between two or more roadways or highways at different levels. Motorways include only grade-separated interchanges.

Interchanges may vary from single ramps connecting local streets to complex and comprehensive layouts involving two or more highways and two, three or even more levels. The basic interchange configurations are shown in Figure 3.

Figure 3: Basic Interchange configurations



Source: AASHTO, 2011.

For a safe traffic operation of interchanges, drivers should be clearly and timely prepared for the required change in driving behaviour (FGSV, 2008). Interchange design should focus on a gradual change in driving behaviour in order to adapt to the modified characteristics of the interchange ramps and to gradually reduce speed. Therefore, interchange design elements should be easily recognisable by drivers, proper warning signage should be installed, adequate level of service should be provided and traffic safety should always be a priority.

4.5 Tunnels

The alignment requirements of motorways imposed by the aim to safely accommodate high speed traffic often result in the construction of tunnels in order to cross obstacles (most commonly a mountain, but also rivers, canals or densely populated areas). Another issue favouring the construction of tunnels has been the increased demand for environmental protection from traffic, including landscape aesthetics and protection from noise and air pollution produced by large traffic streams.

Tunnels are very complex road structures, incorporating increasingly complex equipment and methods of operation that require the deployment of control and supervision systems to handle large amounts of information and accommodate sophisticated management scenarios.

An indicative list of various interacting parameters that need to be considered during tunnel design are (PIARC, 2015):

- urban or non-urban environment,
- geology and hydrogeology,
- human and natural environmental issues,
- traffic characteristics,
- costs (construction and operation)
- operational issues,
- horizontal and vertical alignment,
- cross section,
- safety issues,
- ventilation,
- civil works issues, etc.

The complexity of tunnel design means in particular that approaching the design from a single point of view (e.g. only the alignment, the geology or operating equipment) will most likely result to a less safe infrastructure which is also difficult to operate (PIARC, 2015). All the objectives and constraints relating to operation and maintenance must be taken into account from the preliminary design stage in order to avoid increased operational costs and reduced overall reliability.

Tunnel design and operation in Europe is largely determined by the recommendations of Directive 2004/54/EC of the European Parliament and of the Council (EU, 2004), on the minimum safety requirements for tunnels in the Trans-European Road Network. The Directive includes specific considerations for the design, management and operation of motorway tunnels, aiming to prevent critical events that may endanger human life, the environment and tunnel installations, as well as by the provision of protection in case of accidents.

4.5.1 Horizontal and vertical alignment

The horizontal and vertical alignment of motorways inside tunnels is subject to additional constraints compared to open roads.

Although several restrictions in tunnels may force designers to apply smaller horizontal curve radii, from a road safety point of view, this should be avoided. In tunnels, it is more difficult for the driver to detect curves, accurately estimate curvature and therefore, adjust driving speed accordingly. Furthermore, in the case of a small radius curve on an open road motorway segment, the designer has several tools to inform drivers. However, these tools are not feasible in tunnels (SWOV, 2002).

Geometric characteristics of the horizontal and vertical alignment in tunnels need to integrate the following elements (PIARC, 2015):

- limitation of gradients, which have a major impact on traffic capacity of the tunnel as well as sizing of the ventilation system,
- hydraulic conditions of underground drainage during construction and operation speed,
- reduced lateral clearance, requiring sight distance analysis and particular consideration of horizontal curve radii,
- appropriate choice of radii in order to avoid alternating cross-fall slopes and their impact on water collecting and drainage systems and possible interference with other tunnel equipment.

In EU Directive 2004/54/EC, a maximum gradient of 5% is allowed for tunnels.

An additional important consideration for tunnel design is sight distance. Because of ceiling and walls, sight distances in tunnels are limited in comparison to open road segments. A limited sight distance in motorway tunnels can partly be compensated by supplying the driver with information concerning the current traffic situation in the tunnel, by means of Variable Message Signs (VMS), Lane Control Signs (LCS), Variable Speed Limit Signs (VSLS) and other means of tunnel dynamic signage. The tunnel operator can use information obtained from CCTV and traffic flow measurements to decide on the contents of the messages to the drivers (SWOV, 2002).

4.5.2 Cross section

The shape of tunnel cross section is basically determined by the construction method. A circular cross section is the result of the use of Tunnel Boring Machines (TBM). A horse-shoe shaped tunnel is typical for drill and blast and a square cross section is found in cut-and-cover tunnels (SWOV, 2002).

Dimensioning of the cross section relies to the following parameters (PIARC, 2015):

- traffic volume, nature of traffic and urban / non-urban tunnel, in order to determine:
  - number and width of lanes,
  - headroom (according to type of vehicles),
  - hard shoulders, emergency lanes, lay-bys.
- ventilation (taking into account the space required for ventilation ducts, fans and other equipment),
- evacuation of users and access of emergency and rescue teams,
- length and gradient of the tunnel,
- networks and equipment for operation (e.g. sewer systems, water supply for the fire-fighting system, high and medium voltage cables, operation signalling equipment)
- construction methods and geological conditions.

Very often tunnel designers aim to minimise the area of the cross section in order to reduce construction cost, resulting in many cases in the absence of emergency lanes. In a simulator study (Martens et al., 1998), driver behaviour of subjects over the transition from a wide cross section into a smaller one was studied in open road conditions (control) and tunnel conditions (experimental). Driving behaviour was expressed in terms of speed and of distance between the right road edge line marker and the right side of the car. The experiment revealed that lateral width per se influences driving behaviour and that this effect is stronger in a tunnel. However, the effects on lateral position and speed were found to be relatively small. The authors recommended not to omit the emergency lane in tunnels, and in cases where this is not possible, to include a narrow emergency lane of 1,50m in order to mitigate the negative effects on road capacity and traffic safety.

4.5.3 Safety and operation

The following parameters have a major impact on tunnel safety and operation (PIARC, 2015):

Volume and nature of traffic: As previously stated, traffic volume affects the number of lanes, ventilation and evacuation. It also affects the impact of breakdown vehicles and their management: requirement for an emergency stopping lane, for lay-bys and organisation of particular provisions for repair service. The nature of traffic and type of vehicles affect the evacuation concept (cross-passages, evacuation galleries dimensioning and spacing), according to the expected number of people to be evacuated. Finally, the transfer or not of dangerous goods has an important impact on the ventilation system, on cross section design to accommodate fluid collection and dewatering measures, on diversion routes, on the protection of structures against a major fire, as well as the organisation of emergency services and especially the fire brigade.

Evacuation of users and access of emergency teams: The design of the evacuation system (exits to the outside, cross-passages, under or parallel gallery, shelters or temporary refuges etc.) requires an integrated approach with the ventilation design, volume of traffic, risk analysis, drafting of emergency response plan and construction methods. It is necessary to define the routes in order to ensure the flow of people and to ensure the homogeneity, legibility and calming character of these facilities, taking into account that they will be used by people in stress situations (accident, fire) before the arrival of the emergency services.

Ventilation: Ventilation facilities are essentially designed in order to provide healthy conditions inside the tunnel by the dilution of air pollution and to ensure safety in case of fire by providing efficient smoke extraction. They have to be able to adapt in a dynamic and fast way to numerous conditions in order to address climatic constraints (significant and fluctuating air pressure differentials between tunnel portals) and provide variable operating rates for smoke management in case of fire, according to the development of fire, in order to assist fire-fighting strategies and tunnel evacuation.

Communication with users and tunnel supervision system: Communication with users and supervision has an important impact on tunnel cross section design, as well as on the operating equipment - remote monitoring, detection, communications, traffic management, control and supervision - and the organisation of evacuation.

4.6 Motorway equipment and traffic control devices

Due to the high operating speeds, safe motorway operation requires the installation of highly efficient road equipment and traffic control devices. Specifically:

Road markings: Motorway pavements are fully marked in order to efficiently guide road users. A fundamental requirement for pavement markings is visibility during daylight, at night time and in wet conditions. Night-time visibility is of outmost importance, because during the day, drivers also have other visual clues for optical guidance. Road markings in motorways should be visible from a minimum distance of 75m to 100m (FGSV, 2008). Further optical guidance, wherever required, can be achieved by installing reflective markers on guardrails or posts, or arrow signs in curves.

Previous research (NCHRP, 2006) in the state of California USA, however, investigating the safety effect of the retro-reflectivity of pavement markings and markers, was not able to identify a clear relation. One hypothesis is that drivers compensate by reducing their speed under lower visibility conditions, and maintain higher speeds under higher visibility conditions. Therefore, any effect of the level of brightness of pavement markings may be minimized by driver adaptation to road conditions.

Traffic Signs: Dimensioning and layout of traffic signs on motorways is determined according to the traffic sign regulation of each country. As a general observation, traffic signs should be installed only when required. Traffic restriction and warning signs in particular, should be used only when specific local conditions indicate an increased risk, such as (FGSV, 2008):

- occurrence of traffic merging and/ or diversion in relatively small length of the motorway,
- densely spaced entrance and exit ramps,
- implementation of minimum design values in horizontal and/or vertical alignment, in otherwise smoothly flowing designs,
- record of increased accident rates in a specific section of the motorway.

Informative signs are also of particular importance. A proper balance is required between presenting detailed direction information and not overloading drivers. During high speed driving only a limited amount of data can be realized and processed by drivers; excessive signage may result in driver overload and distraction and ultimately may deteriorate road safety.

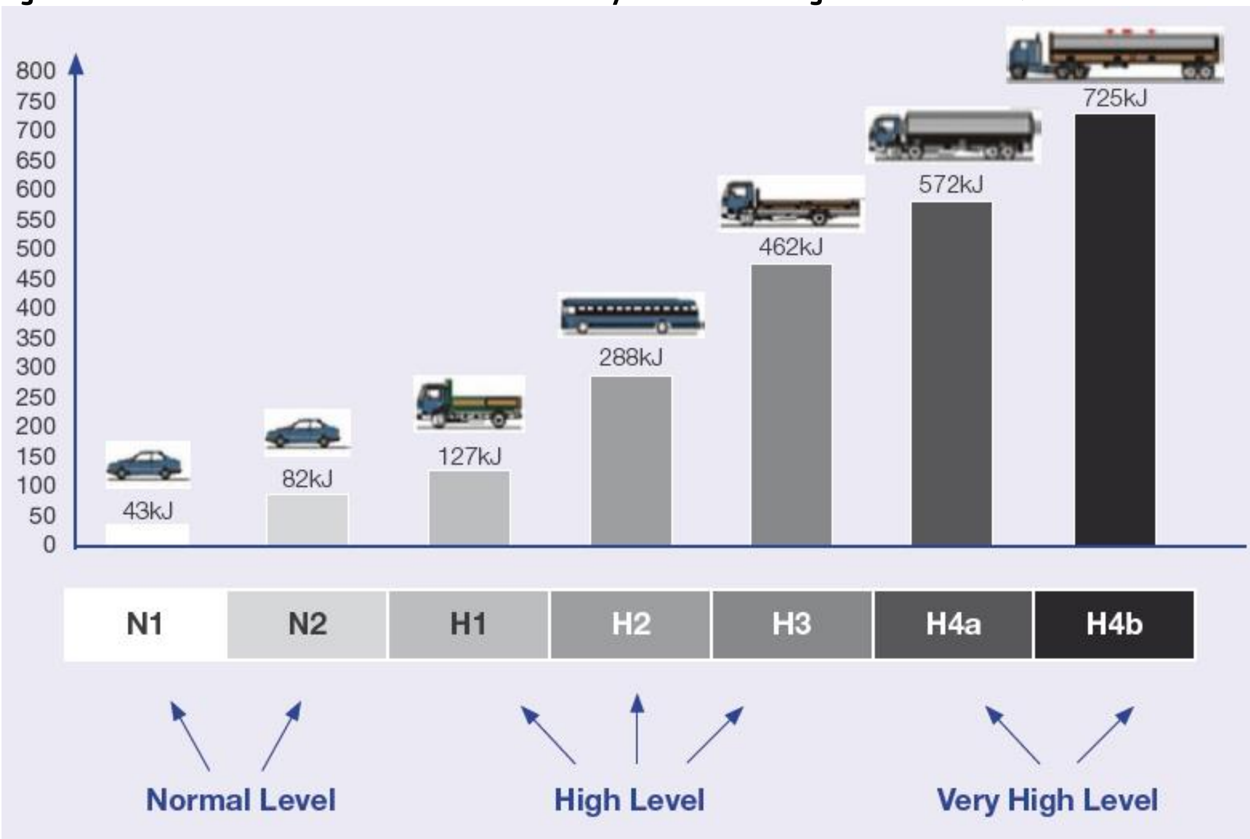
Vehicle restraint systems: Vehicle restraint systems on motorways (safety barriers and guardrails) aim to mitigate accident consequences, both for road users not involved in the accident (e.g. opposite direction traffic flow) and for vehicle occupants (e.g. prevent a head-on crash to rigid roadside obstacles). Prior to the installation of vehicle restraint systems, it should always be investigated if the roadside can be redesigned and potentially dangerous obstacles can be removed.

As of January 1st 2011, all vehicle restraint systems in the EU (including for motorways) need to be certified according to the European Norm EN1317, which specifies common requirements for the testing and certification of such systems. It should, however, be noted that EN1317 does not specify which barrier should be used in each specific case, but it defines the test procedures for classification of the performance and other parameters of each product.

According to EN1317, vehicle restraint systems are classified according to three performance classes: containment level, impact severity and working width. Containment level refers to vehicle type, impact speed and impact angle for the product's crash tests, impact severity to the degree of physical strain on the passengers and working width to the physical deformation of the restraint system.

A graphical representation of the various containment levels, according to crash tests' vehicle type, as specified in the norm EN 1317, is shown in Figure 4:

Figure 4: Containment level of Vehicle Restraint Systems according to norm EN1317



Source: ERF, 2012

Minimum legal requirements for the containment level of safety barriers on motorways differ among EU countries (see Table 3).

Table 3: Minimum legal requirements for the containment level of safety barriers on motorways

Country	Side barrier (except walls & bridges)	Central median barrier	Side barrier on bridges
Austria	H2	H2	H3
Belgium	H2	H2	H4b
Denmark	H1	H2	H3
Finland	N2	N2	H2
France	N2	H1	N2
Germany	H2	H2	H4b
Ireland	N2	H2	H2
Italy	H2	H3	H4b
Netherlands	H2	H2	H2
Norway	N2	N2	H2
Spain	H1	H2	H3
UK	N2	N2	H1

Source: ERF, 2012

A general distinction can be made between rigid vehicle restraint systems (e.g. concrete safety barriers) and flexible systems, such as metal barriers. Rigid systems have the advantage of requiring less space for installation (because they normally do not deform during the impact) and usually cost less to repair after an accident. However, the degree of physical strain to vehicle occupants, especially in passenger cars, is greater in comparison to flexible systems.

Anti-glare panels: Anti-glare panels, typically installed between the opposite directions of traffic, serve to protect drivers from the glare of vehicle headlights or from other sources of light. They are commonly installed in the following cases (FGSV, 2008):

- on motorway sections with alignment that allows glare, e.g. in crest vertical curves, in horizontal curves combined with sag vertical curves, or in sections with different roadway elevations between the opposite directions of travel,
- on motorway sections with high accident rates during night-time,
- on sections with high night-time traffic volumes,
- on long tangent sections, bridges and rest areas,
- at grade-separated intersections with small distance between the ramps and the main motorway.

Motorway fencing: Fencing aims to prevent wildlife from entering the motorway, in order to protect both road users and animals.

Electronic traffic control devices:
The safe operation of motorways is enhanced by a large number of electronic equipment and devices, such as:

- emergency phone network, enabling road users to communicate with the motorway operator,
- Closed Circuit TV (CCTV), for the surveillance of the motorway and the identification of various incidents,
- Variable Message Signs (VMS), enabling the motorway operator to inform road users on various safety related issues (e.g. roadworks, incidents etc.)
- Variable Speed Limit Signs (VSLS), enabling the motorway operator to reduce the speed limit according to traffic conditions or other incidents,
- Over-Height Vehicle Detection (OHVD), to identify and stop vehicles exceeding the maximum permissible height, in order to prevent damage to motorway tunnels and other overhead structures, etc.

A more detailed overview of the above elements on the context of managed (urban) motorways can be found in Section 8 of the present report.

5 Safety benefits of motorways

5.1 Construction of motorways

Motorways exhibit much lower accident rates (injury accidents per million vehicle kilometre) than other road types. A meta-analysis of relevant studies in Norway by Elvik et al. (2009) concluded that accident rates on motorways in Norway were 50% to 81% (according to the examined study and time period) less than on two-lane rural roads. Studies in other European countries (Sweden, Denmark, Finland, UK, Germany, the Netherlands) and USA, also compiled by Elvik et al. (2009), indicate a 70% to 90% lower accident rate in motorways, compared to standard country roads and urban roads.

Box 2: High proportion of traffic on motorways in the Netherlands influences road fatality rates

An intensive period of motorway building during 1970s and 1980s in the Netherlands has resulted in 40% of the national total of vehicle kilometres being travelled on motorways, which have low fatality rates compared with other rural roads. The respective percentage is 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 the 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

Before and after studies indicate that when a new motorway is constructed, the resulting reduction in the number of accidents is not as large as the difference in accident rates might lead one to expect (Elvik et al., 2009). Such studies in Norway (1993), Sweden (1983 & 1991), Denmark (1991), Great Britain (1964 & 1969) and USA (1970 & 1992) have found an average decrease in the number of injury accidents of around 7% (95% confidence intervals: 4% to 9%). This can be explained (Elvik et al., 2009) considering firstly, that not all traffic using the existing roads transfers to the new motorway, and secondly, that the construction of a motorway often generates new traffic, especially when the existing roads had traffic congestion problems. Generally speaking, the extent of accident reduction that can be attributed to the construction of motorways depends to some extent on how existing traffic is distributed between the motorway and the old road network, and on how large the induced traffic is.

5.2 Other motorway characteristics

In addition to the general safety benefits of motorway construction, it is interesting to examine the safety benefits of specific motorway characteristics, not normally found in other road types, such as the existence of central medians, of grade-separated junctions, access control etc.

5.2.1 Central medians

Medians have been found to reduce accident rates in most situations, with the effect being more pronounced for the most severe accidents. However, in most studies, especially for rural areas, results are inconsistent, either affected by publication bias or by confounding variables which are not controlled for (Elvik et al., 2009). As a general observation, medians (with or without safety barriers) increase the distance between opposing traffic flows and as a result change the distribution of accidents by type: reduced numbers of head-on collisions have been reported, but often increased numbers of less severe accidents can also be expected (Elvik et al., 2009; Machata et al., 2017).

5.2.2 Grade-separated junctions

Besides being able to serve large traffic volumes, grade-separated junctions (interchanges) exhibit lower accident rates compared to at-grade intersections. A relevant meta-analysis by Elvik et al. (2009) compared the results of several studies on European countries and estimated the effects of replacing three-legged intersections (T-junctions) and four-legged intersections (X-junctions) by grade-separated interchanges. The results (Table 4) indicate a reduction in the number of accidents in all cases, with the only exception of partly grade-separated junctions (i.e. where there is no at-grade connection between the two intersecting roads, but the connections between ramps and roads are at-grade, instead of acceleration/deceleration lanes) replacing at-grade X-junctions with speed cameras.

Table 4: Safety effect of replacing at-grade junctions by grade-separated intersections

	Percentage change in the number of accidents		
Accident severity	Types of accidents affected	Best estimate	95% confidence interval
T-junction: grade-separated instead of at-grade			
Unspecified	All accidents	−16	(−33; +4)
Injury accidents	All accidents	−24	(−57; +33)
X-junction: grade-separated instead of at-grade			
Unspecified	All accidents	−42	(−52; −30)
Injury accidents	All accidents	−57	(−62; −51)
Property damage only accidents	All accidents	−36	(−50; −19)
Signalised junctions: grade-separated instead of at-grade			
Unspecified	All accidents	−27	(−36; −18)
Injury accidents	All accidents	−28	(−40; −15)
Grade-separated instead of partly at-grade junctions			
Unspecified	All accidents	−15	(−24; −5)
Partly grade-separated junctions instead of at-grade X-junction			
Unspecified	All accidents	−26	(−38; −13)
Partly grade-separated junctions instead of at-grade X-junction with speed camera			
Unspecified	All accidents	+115	(+52; +205)
Partly grade-separated instead of signalised junctions			
Unspecified	All accidents	−22	(−41; +3)

Source: Elvik et al. (2009)

Regarding the effect of different interchange types (see also Section 4.4), lower accident rates have been identified in diamond interchanges than most other types of interchanges (Elvik et al., 2009). However, differences are small and usually not statistically significant. This can be attributed to the simple geometric layout that is recognizable and easily understood by drivers, as well as to the straight alignment of interchange ramps, that naturally exhibit lower accident rates compared to the curved ramps of other interchange designs (trumpet, cloverleaf etc.)

5.2.3 Access control

Accident rates have been found to significantly increase with increasing numbers of private access roads per kilometre of road. Studies in Norway have proposed a relationship between the number of private access roads per kilometre of road and the accident rate as per Table 5. It is obvious that access restriction on motorways can be considered an important factor contributing to reduced accident rates.

Table 5: Relationship between accident rate on national highways and the number of private access roads per km road in Norway

Number of access points per kilometre road	Accidents per million vehicle kilometres
None – motorway class A	0.08
None – motorway class B	0.11
0–5	0.21
6–10	0.27
11–15	0.29
16–30	0.38
Over 30	0.47
City centre areas (over 50)	0.80

Source: Elvik et al. (2009)

5.2.4 Dynamic speed limits

One of the objectives of dynamic speed limits is to improve traffic safety through reductions in mean speeds and in speed variations within and across lanes and between upstream and downstream flows. In a study by Lee et al. (2006), a microscopic traffic simulation model was used to simulate changes in traffic conditions as an effect of variable speed limits. The study results indicated that variable speed limits could reduce accident rates by 5% to 17%, by temporarily reducing speed limits during risky traffic conditions when accident potential exceeded a pre-specified threshold. Rämä (1999) investigated the effects of weather-controlled dynamic speed limits. The results showed that in winter the change of the posted speed limit from 100km/h to 80km/h decreased the mean speed of cars traveling in free-flow traffic by 3,4km/h, in addition to the average mean speed reduction of 6,3km/h caused by adverse weather and road surface conditions. When poor road conditions were difficult to detect (e.g., there was no rain or snowfall or the rain was insignificant), the effect was 1,9km/h higher (i.e., the reduction was 5,3km/h). In addition to the effects on mean speed, lowering of the speed limit decreased the speed variance. De Pauw et al. (forthcoming) did a before-after analysis on the effects of a dynamic speed limit system on the number of crashes. The results showed a significant (-18%) decrease of the number of injury crashes after the introduction of the system. A distinction according to crash type showed an almost significant decrease of 20% in the number of rear-end crashes whereas the number of single-vehicle crashes decreased by 15% (not significant). No effect was found for side crashes.

All the above research findings clearly indicate that motorways exhibit increased road safety levels for road users.

6 Motorway Accidents

Although motorways exhibit reduced accident rates compared to other road types, accidents still occur. Furthermore, as a result of increased vehicle speeds in motorways, accidents tend to be more severe (see also ERSO Traffic Safety Synthesis on Speed and Speed Management).

According to the European Commission (2017), more than 24.000 people were killed in road accidents on motorways in the European Union between 2006 and 2015. This number corresponds to 7% of all road fatalities in those countries. In Table 6, the number of fatalities on motorways by country is presented.

Table 6: Number of fatalities on motorways by country

	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
BE	164	153	139	150	106	120	91	94	108	108
BG	-	-	38	36	-	-	-	-	-	-
CZ	37	48	30	25	28	21	22	25	25	32
DK	16	24	31	24	27	12	8	12	14	16
DE	645	602	495	475	430	453	387	428	375	414
EE	-	-	-	-	-	-	-	-	-	-
IE	11	10	2	4	9	9	5	8	-	-
EL	147	140	120	108	87	81	57	79	56	53
ES	776	618	496	465	418	341	304	294	290	277
FR	296	273	233	225	238	268	223	238	220	298
HR	-	65	67	43	33	23	43	41	23	18
IT	590	526	452	350	376	338	330	321	287	305
CY	10	13	8	7	9	7	3	2	3	6
LV	-	-	-	-	-	-	-	-	-	-
LT	-	-	-	-	-	-	-	-	-	-
LU	6	11	6	36	29	4	7	6	3	3
HU	55	61	54	38	44	49	31	30	27	34
MT	-	-	-	-	-	-	-	-	-	-
NL	-	-	-	83	64	43	68	59	57	81
AT	74	74	71	61	59	46	50	31	36	41
PL	55	53	35	43	28	37	44	40	56	61
PT	84	128	96	89	111	84	58	44	50	61
RO	50	41	21	25	18	16	17	24	21	19
SI	33	37	13	30	19	20	20	16	15	15
SK	15	19	14	9	14	-	-	-	-	-
FI	17	14	9	12	4	11	13	8	8	6
SE	28	25	18	21	24	20	18	21	31	-
UK	189	185	160	132	118	106	89	102	96	111
EU	**3.485**	**3.240**	**2.691**	**2.491**	**2.329**	**2.159**	**1.938**	**1.973**	**1.859**	**2.048**
Yearly change		-7,0%	-16,9%	-7,4%	-6,5%	-7,3%	-10,2%	1,8%	-5,8%	10,2%
CH	31	47	27	34	23	22	63	23	12	21

Source: European Commission Traffic Safety Basic Fact on Motorways, 2017b

It is interesting to point out that the highest percentage of fatalities on European motorways occurred in the 25-49 age group (2015 data), whereas the over 64 age group is less involved in motorway fatalities (15%) than in non-motorway fatalities (27%).

Three types of accidents on motorways are of particular interest: (a) accidents caused by the improper use of emergency lanes, (b) cross-median head-on accidents, and (c) accidents involving wrong way driving.

6.1 Improper use of emergency lane

Accident statistics indicate that a sizeable percentage of accidents on European motorways is related to emergency lanes. The cause of these accidents seems to be the inappropriate use of the emergency lane and the nearside lane (SWOV, 2002). More importantly, the severity of these accidents tends to be significantly higher than of most other accidents on motorways (see also Box 3).

In all EU countries, traffic regulations commonly prohibit the use of emergency lanes for normal operation and regular traffic. The purpose of emergency lanes is (a) to provide the necessary space for emergency stop of vehicles and (b) to be used by emergency services vehicles (police, ambulances, fire brigade).

Box 3: Severity of accidents on emergency lanes

Netherlands: Although multiple accidents on emergency lanes accounted for only 1.5% of injury accidents on Dutch motorways (1992-1995 period), the corresponding share of fatalities was 8%.

United Kingdom: An investigation of accidents involving vehicles using motorway hard shoulders in the UK came to the conclusion that the severity of these accidents was three times higher than the severity of other accidents on motorways.

Source: SWOV, 2002

Vehicles stopped on the emergency lane are a potential hazard. An indication of accident risk on motorways emergency lanes involving a stopped vehicle is the number of stopped vehicles on emergency lanes per 100Km of motorway. A 1987 study in the Netherlands indicated a total of 4.1 vehicles per 100Km (at both sides of the motorway), while a 1997 study found a 10.9 vehicles per 100Km (SWOV, 2002). A further alarming finding of the 1987 study is that for only 3% of the vehicles stopped on emergency lanes on Dutch motorways, the warning triangle was placed. This was attributed to insufficient knowledge of the mandatory use of the warning triangle, unavailability of the triangle, trouble to get out of the car and place the triangle, fear of being run over, and doubt about either the efficiency of the triangle or the necessity to warn other users.

Measures that have been proposed in order to reduce accidents on emergency lanes are (SWOV, 2002):

- installation of rumble strips on the border between the carriageway and the emergency lane,
- widening of emergency lanes,
- information campaigns on the use of emergency lanes on motorways,
- installation of lighting on motorways, especially in sections where emergency lanes and/ or through lanes are narrow.

6.2 Cross-median accidents

Head-on cross-median accidents typically occur when a vehicle crosses the median and crashes with a vehicle travelling in the opposite direction. A head-on accident can also occur when a vehicle inadvertently travels the wrong way in the opposing traffic lanes. The latter scenario is examined in Section 6.3.

Head-on accidents on motorways are usually very severe in nature. According to NCHRP (2009), in 2003, on US motorways there were 366 fatal cross-median head-on accidents, representing approximately 8% of all fatal accidents on motorways. From 1994 to 2002, while fluctuating annually, median-crossover and wrong-way fatalities have increased in the U.S. by 17%. In addition, it appears that a number of cross-median fatal accidents have occurred at locations where some type of barrier was in place.

Head-on cross-median accidents are typically the result of improper driver actions, commonly in combination with other adverse circumstances, such as weather conditions or motorist fatigue. Donnell et al. (2002) identified the following as major contributory factors for median-barrier accidents occurring on Pennsylvania Interstate highways: improper lane changes, driver losing control of vehicle, travelling too fast for weather conditions, exceeding the posted speed limit, and forced vehicle movement or avoidance manoeuvres. According to NCHRP (2009), "*the predominant geometric feature associated with such crashes is the median, including its width as well as the presence (or absence) of a barrier or similar device, and proximity to interchanges. There is evidence that such crashes are associated with high-risk driver behaviors, including excessive speeding and erratic manoeuvres*".

Box 4: Cross-median accidents in the US

- There is one cross-median fatality annually for about every 200 freeway miles.
- An average of 250 people are killed annually in freeway cross-median accidents.
- Cross-median accidents are three times more severe than other highway crashes.
- According to 2003 FARS data, 56 percent of these accidents occur on urban Interstates/ freeways and 44 percent occur on rural Interstates.

Sources: NCHRP, 2009; Stasberg & Crawley, 2005.

Recent experience and research has shown that a comprehensive approach to safety is most effective in creating a safer driving environment and improved effectiveness of safety treatments. Within this context, the following objectives for reducing the number of fatal head-on accidents on motorways have been defined (NCHRP, 2009):

1. <u>Keep vehicles from departing the travelled way</u>

This objective assumes that a vehicle has not left the road and is on the travel lanes or about to stray out of a lane into the median. The proposed strategies include:

i. Installation of left shoulder rumble strips.
ii. Provision of enhanced pavement markings and median delineation.
iii. Provision of improved pavement surfaces.

The strategies involve either keeping the vehicle on a travel lane through enhanced traffic control devices that engage the driver's attention or by the installation of improved pavement capability to reduce skidding and reduce the potential of leaving the roadway. In addition, if a driver strays from the road, the provision of left median shoulder rumble strips aims to give an audible alert to the driver so that it is possible to regain control.

2. <u>Minimize the likelihood of head-on accidents with an oncoming vehicle</u>

This objective considers the situation in which the vehicle has already left the lane and is in the median. The proposed strategies include:

i. Provision of wider medians.
ii. Improvement of median design for vehicle recovery, including improvement of pavement edge drop-offs, provision of paved median shoulder and design for safer slopes.
iii. Installation of median barriers for narrow-width medians.
iv. Implementation of channelization, signing and striping improvements at interchanges susceptible to wrong-way movements.

The aforementioned strategies involve preventing the vehicle from crossing over into the opposite direction of travel, and helping to redirect the vehicle in the direction of flow. The objective is not the prevention of an accident, since the vehicle has already left the travelled way, but minimizing the potential of a severe head-on accident. Central to the objective is utilization of the median. There are several principal purposes and advantages in providing a median. Medians separate opposing traffic streams, provide a recovery area for out-of-control vehicles, and provide a place for vehicles to stop in the event of an emergency. In addition, some medians and median barriers can potentially reduce oncoming headlight glare from vehicles.

3. <u>Reduce the severity of median-barrier crashes that occur</u>

This objective includes a strategy, namely the improvement of design and application of barrier and attenuation systems, aiming at the likelihood of reducing the severity of the accident rather than preventing it.

4. <u>Enhance enforcement and awareness of traffic regulations</u>

This objective includes the following strategies:

i. Designate "Highway Safety Corridors".
ii. Conduct public information & education campaigns.

In some cases, cross-median collisions are symptoms of problems unique to a specific motorway corridor or location. Evidence of this may come from a review of the traffic volume and geometry of the problem corridor compared to other similar locations in the state. Understanding why one corridor experiences cross-median collisions when other comparable roadways do not, may require more in-depth study but such an effort may lead to more effective and less costly solutions than, for example, median barrier placement. The reasons may relate to their location, climate, the local driving population, or other factors not directly related to roadway design. One strategy that may be considered to address these roadways is to designate the facility as a "Highway Safety Corridor," and apply more frequent enforcement, low-cost engineering improvements, and education efforts to enhance safety along the corridor.

Also, like many other safety problems, the problem of cross-median accidents can be effectively enhanced with a properly designed public information & education campaign, through television, radio, local newspapers or the internet.

5. Improve coordination of agency safety initiatives
In order to plan efficient safety measures, accurate accident data along with periodic updating are required. Updated information regarding the geometric conditions of the roadway is essential and the following criteria have been specified as important for assessing the quality of accident information: timeliness, consistency, completeness, accuracy, accessibility and data integration.

6.3 Wrong-way driving accidents

A wrong-way accident is defined as a traffic accident caused by a wrong-way driver, who is a driver travelling in the wrong direction along a one-way street or on a physically separated motorway. This section deals with wrong-way driving accidents on motorways alone, where, normally, entry points for wrong-way driving are the exit ramps at interchange areas.

Similarly to cross-median motorway accidents, although the number of wrong-way driving accidents is relatively limited, their consequences are much more severe than the consequences of other motorway injury accidents.

Box 5: Prevalence of wrong-way driving accidents on motorways

Netherlands: An average of 22 wrong-way accidents per year was estimated for the 1991-1997 period, reduced to 7 wrong-way accidents per year for the 1998-2003 period (SWOV, 2009).

USA: According to FARS data, a total of 1.753 people died in wrong-way accidents in US motorways from 1996 to 2000, with an average number of 350 fatalities per year (ICT, 2012).

Switzerland: An average of 27 wrong-way accidents per year was estimated in the 2000-2004 period (Scaramuzza & Cavegn, 2007).

Japan: An average of 31 wrong-way accidents per year was estimated for the 1997-2000 period (ITARDA, 2002).

6.3.1 Accident location and conditions

On motorways, wrong-way driving accidents occur mainly on the main carriageway. A study (Blokpoel & De Niet, 2000) investigating wrong-way driving accidents in Dutch motorways between 1983-1998 reported that 79% took place on the main carriageway, 5% on merging lanes, and 17% on entry and exit ramps. One would expect such accidents to have occurred mainly during periods of bad weather or darkness, but this was not exactly the case. The majority of the wrong-way driving accidents (80%) occurred in dry weather and a considerable proportion of them (40%) occurred during daytime. However, the night time share of wrong-way driving accidents (0,2%) was indeed twice as large as the daytime share (0,1%).

A study in North Carolina (Braam, 2006) found that 33% of the wrong-way driving accidents occurred during dark conditions (at night without street lighting), and 28% occurred at night on motorways with streetlights.

6.3.2 Characteristics of the wrong-way driver

Several studies (ICT, 2012; SWOV, 2007; Cooner & Ranft, 2008; Vicedo, 2006) indicate that young drivers and older drivers are over-represented in wrong-way accidents. In Japan, older drivers contributed to 29% of wrong-way accidents although they contributed to only 4% in total highway accidents (ITARDA 2002). In the Netherlands (SWOV, 2007), of all those of 70 years old and older who had been involved in an accident, 0,7% were wrong-way drivers, whereas this was only 0,03% of younger drivers (1983-1998 data). In other words, the proportion of drivers of 70 years old and older who caused an accident by wrong-way driving is about 23 times higher than those of the other age groups.

The driver's gender hardly plays a role in wrong-way driving. The average proportion of women causing a wrong-way driving accident in the period 1991-1997 in the Netherlands was 19%, but this is equal to the proportion of women drivers in all injury accidents (SWOV, 2007).

A frequent contributory factor in wrong-way driving accidents on motorways, especially for young or medium-aged drivers, is driving under the influence (DUI) of alcohol or drugs. According to SWOV (2007), in the period 1983-1990, alcohol played a role in 45% of the wrong-way driving accidents, and in the 1991-1998 period, in 20% of them. During the entire period 1983-1998, 56% of the 25-54 year old wrong-way drivers were under the influence of alcohol, 44% of the 18-24 year olds, and only one wrong-way driver in the age group of 70 years and older was under the influence of alcohol. For the period 1991-1997, for all age groups alcohol use played a role with about 2% of all drivers in non-wrong-way accidents, but for the wrong-way accident drivers this percentage was much higher. Especially for the age group 40-54, 38% of the wrong-way drivers were under the influence of alcohol.

In the US (ICT, 2012), the percentage of wrong-way driving accidents attributed to DUI ranges from 43% in North Carolina to over 60% in Texas and New Mexico.

6.3.3 Causes of wrong-way driving

According to ITARDA (2002), the causes of wrong-way driving differ between age groups. Most of the accidents caused by drivers in the young and middle-age range were brought about by inattention, while most accidents caused by drivers in the senior age range occurred because of some physical illness such as dementia or not understanding how to use the highway facilities.

According to SWOV (2007) the most common mistakes were (a) choosing the exit road instead of the entry road when joining from a non-motorway, and (b) turning and driving against the traffic.

Driving up an exit road is usually an error and generally happens to older drivers who, when it's dark, turn left too early. The cause of this error is often a problem with processing (visual) information. For example, if the exit road is very conspicuous and the view of the entry road is poor, drivers may be 'lured' to the exit road. Other contributing factors are faded road marking and missing or incorrectly positioned road.

On the other hand, mostly young drivers were found to begin a wrong-way journey by turning. In general, these drivers deliberately committed an offence in order to correct a previous mistake (e.g. missing an exit road) or to shake off pursuing police. These offences may involve underestimation of the risks of wrong-way driving. Another possibility is that drivers do not recognize a dual carriageway as such, in which case they made an error (SWOV, 2007).

In ICT (2012), the contributing factors for wrong-way driving accidents have been coded in six distinct categories, as in Table 7.

Table 7: Contributing Factors for wrong-way driving accidents in motorways

Categories	Description
Traffic violation	• Driving under the influence (DUI) • Intentional reckless driving • Suicide • Test of courage • Escaping from a crime scene • Avoiding traffic congestion
Inattention	• Falling asleep at the wheel • Carelessness, absent-mindedness, distraction • Inattention to informational signposts
Impaired judgment	• Physical illness • Elderly driver • Drivers with psychiatric problems
Insufficient knowledge	• Lack of understanding of how to use the highway • Unfamiliar with the infrastructure • Loss of bearings
Infrastructure deficiency	• Insufficient lighting • Insufficient field view • Heavy vegetation
Others	• Inclement weather

Source: ICT (2012)

6.3.4 Interchange type and wrong-way driving

Past research (Howard, 1980; Copelan, 1989; Moler, 2002; Braam, 2006; Cooner et al., 2004; NCHRP, 2009) has shown that some ramp and interchange types are more problematic and susceptible to wrong-way movements. Some conclusions from different studies are summarized in ICT (2012) as follows:

- Partial cloverleaf interchanges are identified as the most probable locations for wrong-way entries to the motorway, with the side-by-side on- and off-ramp configuration contributing to driver mistakes. In some cases, concrete barriers may separate the looping ramps so that drivers cannot see the entrance ramp on the barrier's other side (Howard, 1980; Moler, 2002; NCHRP, 2009).
- Full cloverleaf interchanges are the most desirable type of interchange to avoid wrong-way movements, especially if proper traffic control devices are used on the overcrossing bridge to keep motorists on the proper side (Howard, 1980; Moler, 2002; Braam, 2006).
- Trumpet interchanges are more susceptible to wrong-way movements, while such problems are rare in full cloverleaf and full-diamond interchanges (Howard, 1980; Copelan, 1989).
- A full-diamond interchange minimizes driver confusion and wrong-way movement. However, sometimes drivers will mistake an off-ramp of a diamond interchange for a frontage road parallel to the ramp or highway, mistakenly turning left from the overcrossing street to the off-ramp (Howard, 1980; Moler, 2002; Braam, 2006).
- Left-side off-ramps are characterised by increased risk for wrong-way motorway entrances, because drivers naturally expect to enter the motorway using a right-turn and may mistakenly travel the wrong way from the exit of the left-side off-ramp (Howard, 1980; Cooner et al., 2004).

6.3.5 Countermeasures

The common countermeasures for wrong-way driving include engineering (signage, pavement marking, roadway geometry, and ITS), education (training), and enforcement (emergency response, confinement, and radio messages) (ICT, 2012; ICT, 2014). A synopsis of commonly applied countermeasures is presented in Table 8.

Table 8: Common countermeasures for wrong-way driving.

Engineering			
Signing	**Pavement Marking**	**Geometric Improvement**	**ITS Technologies**
▪ Implementing standard wrong-way sign package ▪ Improved static signs ▪ Lowering sign height ▪ Using oversized signs ▪ Mounting multiple signs on the same post ▪ Applying red retro-reflective tape to the vertical posts ▪ "Freeway Entrance" sign for all on ramps (ensure right-way driving)	▪ Stop bar ▪ Wrong-way arrow ▪ Turn/through lane-only arrow ▪ Raised pavement markers ▪ Short dashed line to delineate through turns	▪ Entrance/exit ramp separation ▪ Raised curb median ▪ Longitudinal channelizers ▪ Change ramp geometrics: ❖ Obtuse angle ❖ Sharp corner radii	▪ LED illuminated signs ▪ Dynamic message sign to give warning to right-way drivers ▪ Use existing GPS navigation technologies to provide wrong-way movement alerts ▪ Provide consistent messages or alerts that are intuitive to the driver
Enforcement			
▪ Alert law enforcement agency ▪ DUI enforcement ▪ Portable spike barriers to stop WW drivers; implemented by Harris County Toll Road Authority (HCTRA), Texas			
Education			
▪ Public awareness and understanding of: ❖ Basics of road designs and interchange types ❖ Actions (witnessing a wrong-way driver) ▪ Focus groups: ❖ Older drivers ❖ DUI drivers ❖ Young drivers			

Source: ICT (2012)

The DO NOT ENTER sign is the most universal and recognizable countermeasure for wrong-way driving. Supplementary signs, such as WRONG WAY, GO BACK etc. are also used in some countries for deterring wrong-way movements.

Besides the countermeasures of Table 8, if there is a wrong-way driver on a motorway, it is important to take measures to protect other road users (SWOV, 2007). Such measures are mainly aimed at separating the wrong-way driver from the other traffic, for example by stopping the other traffic in front of an open bridge or closed tunnel, or by clearing the left-hand lane on which 80% of the wrong-way drivers are driving. The effects and cost-effectiveness of these measures are yet unknown.

7 Road safety and congestion on motorways

Traffic congestion obviously affects road safety. However, the actual relationship between congestion and safety is not obvious, and relevant studies indicate mixed results. Congestion might affect road safety due to decreased speed (less severe accidents), high degrees of speed variation within and between lanes increasing the complexity of driving (more accidents), or by creating stress (detrimental for driver behaviour). The general perception is that accident rates increase with increasing congestion levels, whereas severe accidents do not increase. Recent review studies (Filtness & Papadimitriou, 2016; SWOV, 2010) indicate that the results of different relevant studies are not consistent. Some studies indeed find that high volume to capacity (V/C) ratios result in higher accident rates but less severe accidents, while others report fewer single-vehicle crashes, but the effect on multi-vehicle crashes is not consistent across studies. Studies investigating congestion based on speed or travel time generally find congestion to increase crash frequencies, but this is not found in all conditions in all studies.

On the other hand, the effects of changing flow conditions occurring when traffic starts to become congested seem to be more consistently documented (SWOV, 2010). Studies suggest that accident likelihood increases as speed variability increases (a typical indicator for unstable traffic conditions). Also large speed differences between lanes and density variability seem to increase accident likelihood.

Accident severity seems to decrease with increasing volumes (or V/C ratios). Golob et al. (2008) report that accident severity does not seem to change during the transition from free flow to congested conditions, yet it decreases once traffic is congested. In a recent review and meta-analysis of real-time traffic characteristics related to accident risk, based mainly on case-control studies conducted on motorways, Roshandel et al. (2015) found that a higher coefficient of variation of speed (the standard deviation of speed divided by average speed) downstream was associated with increased risk of crash occurrence. In a review of the literature on the relationship between speed dispersion and road safety, Elvik (2014) also found that speed dispersion is associated with increased accident risk. Furthermore, studies seem to show consistent results with regard to accident type. Rear-end accidents are more likely to occur during unstable conditions. Shi et al. (2016) report that both congestion (speed-based), and speed variation are related to higher numbers of damage only and slight/severe/fatal injury crashes, especially during peak-hours.

According to Golob et al. (2008), once traffic is fully congested on all motorway lanes, accident severity is greatly reduced. Under these conditions, the most prevalent accident type is collision with (fixed) objects. On the other hand, when only the left and interior lanes are congested, rear-end and side-impact accidents are more likely.

Finally, there is also a relationship between congestion levels and route choice. In the case of a congested motorway, drivers may follow alternative routes attempting to reach their destination faster. This route choice may be based on the driver's familiarity with the network or on information provided by either variable message signs or in-vehicle systems (SWOV, 2010). As indicated in Section 5 of the present web text, motorways are significantly safer than secondary roads. Consequently, when traffic diverts away from congested motorways and into secondary roads, a safety problem might arise.

8 Managed (urban) motorways

Continued growth in travel on congested urban motorways exceeds the ability of agencies to provide sufficient solutions and alternatives based on traditional roadway expansion and infrastructure improvement projects. Several countries are implementing managed motorway concepts to improve motorway capacity without acquiring more land and building large-scale infrastructure projects.

'Managed motorways' is the term used to describe urban motorways that have intelligent information, communications and control systems (ITS tools) incorporated in and alongside the road. These include coordinated on-ramp signalling, variable speed limits, lane control, incident detection and traffic flow data, traveller information and closed circuit television surveillance (Austroads, 2014b; DaCoTA, 2012). A further typical characteristic of managed motorways is hard shoulder running. Managed motorways increase journey reliability and throughput of a motorway by speed management and increase capacity by shoulder running (FHWA, 2011).

The operational objectives for managed motorways are to provide integrated traffic management that (Austroads, 2014b):

- Optimises safety, throughput and travel speed by minimising the possibility of flow breakdown and congestion.
- Provides travel time reliability by reducing variability from day to day.
- Provides traveller information to inform motorists of traffic conditions on the motorway.
- Provides integrated and effective management of traffic during incidents with lane use and speed control in the highest priority sections of the route.
- Manages vehicle speed and speed differential between vehicles to improve safety during periods of congestion or queuing.
- Provides integration with arterial road operation to optimise operation of the overall road network (motorway and other arterial roads).

The basic elements of managed motorways are presented in Table 9, classified according to their functional purpose (intelligence, control or information).

Table 9: Basic elements of managed motorways.

Intelligence	Control	Information
Vehicle detection equipment. CCTV cameras. Incident detection: ▪ image processing systems ▪ traffic data algorithms. Environmental monitoring equipment ▪ weather ▪ noise ▪ emissions. Travel time tracking equipment.	Coordinated ramp signals (CRS). Variable speed limits (VSL). Lane use management systems (LUMS).	Advance motorway condition information signs (AMCIS): ▪ various purpose-built signs on approach roads to motorway. Motorway condition information signs (MCIS): ▪ various purpose-built signs on motorway. **Variable message signs (VMS).** Non-roadside information sources: ▪ radio ▪ in-car systems ▪ websites/social media ▪ CCTV on website ▪ smart phone/smart TV apps.

Source: Austroads (2014b)

The operation of managed motorways operation relies on the integration of the three primary functions of intelligence, control and information (Austroads, 2014b). The **intelligence function**, including traffic data collection, is the foundation of the managed motorway, informing the control and information functions as well as performance monitoring. **Control functions** use the information from the intelligence function to optimise motorway performance, thus maximising safety, reliability and capacity. The **information function** assists road users in making informed decisions about their travel (e.g. regarding route choice and travel time). Field provision of information is particularly important during unusual conditions such as incidents.

Managed motorway strategies are synergistic and are most effective when applied in an integrated and dynamic system (FHWA, 2011). The coordination between these three functions is achieved via the **traffic management centre** (TMC). TMC plays a key role in active management of the motorway network and interacts with all the management tools.

Box 6: Managed motorways case studies.

Variable speed limits in Barcelona: An over-lane speed and lane control signal system is in place in Barcelona. Overhead gantries are located about every 500m. Two algorithms are used, one for traffic congestion and control and the other for air quality mitigation. The traffic congestion and control algorithm is most typically used. The lane control signals can close a lane (using a red X) to move traffic out of the path of an accident. Speeds are reduced in 10-km/h increments, and 40 km/h is the minimum speed. Automated enforcement is conducted using cameras and mailed tickets. A decrease in accidents has been observed.

Reversible lane in Madrid A6: A single contraflow lane has been implemented on a two-lane separated, four-lane carriageway for weekend and summer traffic. The reversible lane is for high-occupancy vehicle (HOV) traffic only with one grade-separated entrance point. Transition from two-lane single direction to contraflow operation is via manual transition using handplaced traffic cones.

Hard shoulder running in Hessen: Hard shoulder running was first implemented in 2001. Frankfurt operates 65km of hard shoulder running. Hard shoulder control is usually integrated with line control systems. Both static and dynamic signs are used. The static signs have the arrows on a rotating drum that is changed depending on whether hard shoulder running is allowed.

Source: FHWA (2011)

An overview of the managed motorway elements is presented below, adapted mainly from Austroads (2014b) and FHWA (2011).

8.1 Intelligence elements

Vehicle detection equipment: Vehicle detection equipment provides volumes, speed, occupancy (proxy for density) and classification on a lane-by-lane basis. The information is the basis of monitoring and control for the motorway and is made available to third parties for incorporation in commercial applications.

CCTV cameras: An actively managed motorway requires full CCTV coverage with pan/ tilt/ zoom camera capability for traffic monitoring operations as well as assisting in lane use and incident management. Separate cameras are generally required for mainline monitoring and monitoring of the ramp signalling and they are a useful tool in congestion management, including assessment of congestion on arterial road approaches to the motorway. CCTV is essential for monitoring of ramp queues and fine tuning the ramp signals' operations. They are also used to identify driver behaviour and operational issues such as incidents and planned events, while CCTV images are shared with key incident and emergency management partners.

Incident detection capabilities: Incident detection can take the form of either direct detection (e.g. image processing systems) or algorithms applied to traffic data which flag sudden changes in mean speeds, flows and occupancies.

Environmental monitoring: This includes equipment that monitors environmental conditions such as temperature, wind speed and water levels and, in response to adverse conditions, activates equipment such as pumps and warning signs. Traffic noise and emissions can also be monitored for the purpose of reporting and future planning.

Travel time tracking equipment: Tracking equipment can track vehicle movements for travel time calculations and is also useful for determining origin-destination patterns.

8.2 Control elements

Coordinated ramp signals: Best practice dynamic control allows for ramp signals to operate in an isolated manner or, when needed, engage upstream ramps in a master/slave relationship. When ramp meters are coordinated it improves the ability to manage the mainline motorway flow. By metering inflows from a group of ramps upstream, arrival demand at a critical bottleneck can be managed to match the capacity of the bottleneck. Coordinated ramp metering also has the capability of balancing the queues and wait times between ramps, thereby sharing the delays across several ramps. Furthermore, ramp signal coordination can reduce the likelihood of queue overflow on short ramps by transferring delay to ramps with more storage.

Variable speed management: Variable speed limit (VSL) systems on managed motorways operate to activate lower speed limits appropriate to the travelling conditions with the aim of improving road safety. In Britain for example, results of evaluation of a Motorway Incident Detection and Automatic Signalling system (DaCoTA, 2012) showed that after detecting the presence of stationary traffic on a motorway, setting a signal with an advisory 50mph speed limit resulted in a net reduction of 18% in personal injury accidents.

VSL can also assist in increasing throughput by optimising speed and headway before flow breakdown occurs. To ensure optimum outcomes, a VSL system should be interfaced with the coordinated ramp signal system, if this is provided.

Conditions when VSL may be initiated can relate to congestion, an incident or other event, roadwork or environmental conditions such as high wind speeds affecting traffic operation on a bridge.
Improved safety by variable speed limits is achieved by:
- reducing the speed differential between vehicles
- minimising lane changing and braking caused by speed differential
- increasing time for drivers to react to changing conditions
- reducing the severity of an accident if an impact does occur.

Lane use management (LUMS): A lane use management system (LUMS) - also known as junction control - allocates and manages lane use across the roadway and is particularly useful during incidents and roadwork (Austroads, 2014b). The operation of lane use signs provides traffic management to improve safety during abnormal operation. LUMS includes speed management and should be supported by the use of mainline variable message signs.

Another application of junction control, besides incident management, is the dynamic allocation of lane access on mainline and ramp lanes in interchange areas where high traffic volumes are present, and the relative demand on the mainline and ramps change throughout the day (FHWA, 2016). For off-ramp locations, this may consist of assigning lanes dynamically either for through movements, shared through-exit movements, or exit-only. For on-ramp locations, this may involve a dynamic lane reduction on the mainline upstream of a high-volume entrance ramp and/or providing an additional lane for the on ramp. Volumes on the mainline lanes and ramps are continuously monitored, and lane access is dynamically changed based on the real-time and anticipated conditions. Implementing junction control may involve narrowing lanes, and/or part time use of the ramp and/or mainline shoulder thereby resulting in a narrow or no shoulder during junction control operation.

8.3 Information elements

An overall traveller information strategy for potential motorway users should consider three time periods for the provision of information:

- pre-trip (e.g. before leaving home or work)
- en route but before entering the motorway
- en route, after entering the motorway.

Real-time traveller information informs motorists about current or future traffic conditions and allows drivers to choose the most efficient mode and route to their destination. Alternatively, they may choose to delay their journey or not take it at all.

Traveller information systems use traffic data and other traffic management information to provide timely and detailed information about travel time, congestion, traffic incidents, roadwork, special events and the weather (if applicable), to improve safety and travel time predictability. This can make the road network more resilient, enable drivers to make better choices and can also assist in reducing congestion.

The effective operation of automated on-road traveller information contributes to the overall provision of a traveller information system for a managed motorway that may also include media reports and web-based information. As well as fulfilling a need for day-to-day travel information, the system and facilities provide valuable information and assist in traffic control as part of an overall communications and management plan associated with special or periodic events.

The purpose of the traveller information system is to display real-time traffic and travel information and information relating to changing travel conditions. On-road real-time traveller information includes the use of various types of signs to display a range of sign messages appropriate to the travel conditions. The motorway management system manages traffic devices that operate in default mode for travel information as well as providing special information during incidents or congestion.

These systems are integrated for coordinated operation and consistency of messaging, as well as providing consistent message libraries, graphics and abbreviations.

Traveller information components: Traveller information includes travel time and traffic condition information as well as information relating to incidents, roadwork, closures, prevailing weather conditions, etc. Once on the motorway, this is provided on both VMS and motorway conditions information signs (MCIS).
Non-roadside traveller information on traffic conditions and travel times can come from various sources including:

- Radio: it can reach road users both before and during their trip but road jurisdictions generally have limited control over content and timing of messages. In tunnels however, radio re-broadcast facilities can enable a control room to take over commercial radio broadcasts when conditions in the tunnel warrant informing drivers.
- In-car systems: the use of in-car navigation systems with travel time and dynamic routing information is growing and is expected to have a higher penetration rate in the near future.
- Websites and social media: pre-trip travel information on websites and social media is useful but should form part of a broader network-wide travel information strategy.
- CCTV on website: near-live images of traffic can be streamed to a website from dedicated fixed CCTV cameras installed at various locations around a road network. The website may only show one still image every two to five minutes but these images provide an indication of the current level of service of the road. These images can also be incorporated into third party commercial applications.
- Smart phone/TV apps: there are several map-based apps which can be downloaded onto smart phones or smart TVs which provide dynamic routing information similar to that provided by in-car navigation systems. Some of these apps are community-driven, providing routing and real-time traffic updates sourced from users' driving times.

Variable message signs (VMS): Variable message signs (VMS) increasingly allow a range of information to be conveyed to motorists, and are being used in advance of and on motorways as an alternative to purpose-built AMCIS and MCIS. The range of information goes beyond travel time and traffic conditions, and can include warnings of hazards or disruptions with details of actions to take (e.g. merge left), or forthcoming events affecting motorway travel. VMS can also assist road users to make informed decisions on route choice based on real-time conditions (travel time and traffic condition) and future significant events.

Advance motorway condition information signs (AMCIS): AMCIS are intended to assist motorists in making route choices before entering the motorway. These signs include a range of purpose-built signs placed on approach roads in advance of the motorway entrance. Signs that have been used include variable displays (sometimes embedded in direction signs) indicating motorway traffic conditions as light/medium/heavy, or as travel times in minutes to specific destinations; in addition, sign displays may be colour coded e.g. green means light traffic, red means heavy traffic. Local sign designation may apply – for instance, in Victoria, advance travel time signs are referred to as 'real-time information signs'.

<u>Motorway conditions information signs (MCIS):</u> MCIS are intended to assist motorists in making route choices when on the motorway. These signs include a range of purpose-built signs placed on the motorway, generally with similar functionality to AMCIS (destinations, travel times, traffic conditions, and colour-coding). Local sign designation may apply – for instance, in Victoria, a specific style of motorway travel time signs is referred to 'drive time'.

8.4 Hard shoulder running (or "plus lane")

Hard shoulder running is a means of providing an additional traffic lane during periods of congestion. On some motorway segments, mainly in England, Germany, the Netherlands, and more recently in the US, the shoulder is used dynamically to create an additional travel lane when conditions are appropriate. When the travel lane is added on the outside edge (e.g., right side for Germany, US and the Netherlands, left side for England), "hard shoulder running" is the term generally used. When the additional lane is on the inside edge, the term "plus lane" is normally used (FHWA, 2011).

Gantries that include speed and lane control signs are provided in these sections and usually show a green arrow when the lane is available for use and a red cross when it is closed. The signs can also show the appropriate speed limit for when shoulder running is allowed or the plus lane can be used.

The need to ensure that safety is not compromised by the loss of the hard shoulder means that lower speed limits are required while this lane is in operation. Initial trials in Great Britain (DaCOTA, 2012; FHWA, 2011) in M42 motorway applied speed limits of 50mph (compared to the limit of 70mph for normal running), but this has subsequently been increased to 60mph, with a better overall performance than 50mph and equivalent safety characteristics. Dutch rush hour lanes typically have speed limits set at least 20km/h lower than the normal limit (In t' Veld, 2009). In Germany, when a paved shoulder is converted to a travel lane, a reduced speed limit of 120km/h is considered (from a normal speed limit of 130 to 150km/h). If reallocation of the roadway for hard shoulder running reduces lane widths to less than 3,5m, a speed limit of 100 km/h is instituted (FHWA, 2011).

In Great Britain, emergency refuge areas are provided at 800m intervals, next to the hard shoulder running lane and a roadside telephone link is provided to the Regional Control Centre. In most other countries applying hard shoulder running, emergency refuge areas are also added.

Different approaches are considered for shoulder running through ramp junctions (FHWA, 2011). In England, initial operations of shoulder running used only shoulder segments between ramps (i.e., the shoulder functioned as a lane gain or lane drop at each interchange). In 2009 England implemented a pilot trial allowing through junction running on the M42 motorway at certain locations to increase capacity at key bottlenecks.

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Notes

1. Country abbreviations

Belgium	BE	Italy	IT	Romania	RO
Bulgaria	BG	Cyprus	CY	Slovenia	SI
Czech Republic	CZ	Latvia	LV	Slovakia	SK
Denmark	DK	Lithuania	LT	Finland	FI
Germany	DE	Luxembourg	LU	Sweden	SE
Estonia	EE	Hungary	HU	United Kingdom	UK
Ireland	IE	Malta	MT		
Greece	EL	Netherlands	NL	Iceland	IS
Spain	ES	Austria	AT	Liechtenstein	LI
France	FR	Poland	PL	Norway	NO
Croatia	HR	Portugal	PT	Switzerland	CH

2. This 2018 edition of Traffic Safety Synthesis on Motorways was written by Anastasios Dragomanovits, National Technical University of Athens (NTUA).

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