Tunnel Road Design
Junctions In and Near Tunnels in Freeways

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ABTRACT

An analysis was carried out to determine in which situations and under what conditions feeding into, exiting and merging into traffic in or near tunnels is safe. Based on the traffic flow process and risk calculation theories, the minimum distance to be maintained between junctions and the tunnel entrance or exit is determined. The minimum distances are composed of a combination of the turbulence distance of so-called convergence and divergence sections, and the distance within which road users are fixated on the tunnel entrance or the distance that road users need to become accustomed to the transition from light to dark (or vice versa). For instances where these minimum distances cannot be respected, risk compensating measures must be taken.

Keywords

Tunnels, traffic safety, traffic flow, junctions, entrance ramp, exit ramp.

1. INTRODUCTION

Due to spatial limitations, quality of life issues and the fact that environmental limits have been reached, the use of tunnels is receiving increased attention. The Leidsche Rijn tunnel, the A2 through-road in Maastricht, the Zuidas urban development area in Amsterdam and the debate surrounding the tunnel as part of the connection between the A6 and the A9 under the Naardermeer wildlife area, are examples of this.

Since many tunnels are being constructed in or planned for urban areas, junctions are increasingly located in close proximity to or even within tunnels (figure 1). The risks involved in traffic merging, exiting or weaving within or close to a tunnel is assumed greater than it is in situations where this is not the case.

For tunnels with junctions in or near the tunnel it is important to determine the magnitude of the risk. It is then possible to determine how the risk can be reduced to an acceptable level through road design or equipment of the tunnel, and at what cost. At this point in time, clear guidelines for dealing with situations in which junctions are planned close to or in a tunnel are still lacking, however.

ARCADIS was commissioned by the Directorate-General for Public Works and Water Management to carry out a study in this area that resulted in the report ‘Wegontwerp in tunnels, convergentie- en divergentiepunten in en nabij tunnels’ (1). The results of this study were used to create a new design guideline. Although this guideline focuses on Dutch characteristics, the principles can be used for international practice.

The results of this study are summarised in this contribution. Section 2 describes the study approach. In section 3 actual situations are presented. Research, risk analyses and guidelines concerning tunnels and junctions are described in section 4. Section 5 deals with the minimum distances between junctions and tunnels. Compensating measures for situations which doesn’t meet the minimum distances are presented in section 6. Finally, in section 7 the conclusions and recommendations are given.

FIGURE 1 The Roer River Tunnel (left) and the Södra Länken Stockholm (right)

2. STUDY APPROACH

To facilitate the exchange of traffic between a freeway and another road, the Dutch road design guidelines distinguish so-called convergence and divergence sections. Table 1 identifies the different types.

TABLE 1 Types of convergence and divergence sections

Convergence Section	*Divergence Section*	*Combination*
Entrance ramp	Exit ramp	Weaving section
Merging Lane	Fork	
Lane reduction	Additional Lane	

Figure 2 displays the possible combinations of convergence and divergence sections and tunnels. The conditions under which these combinations are acceptable, are subject of this study.

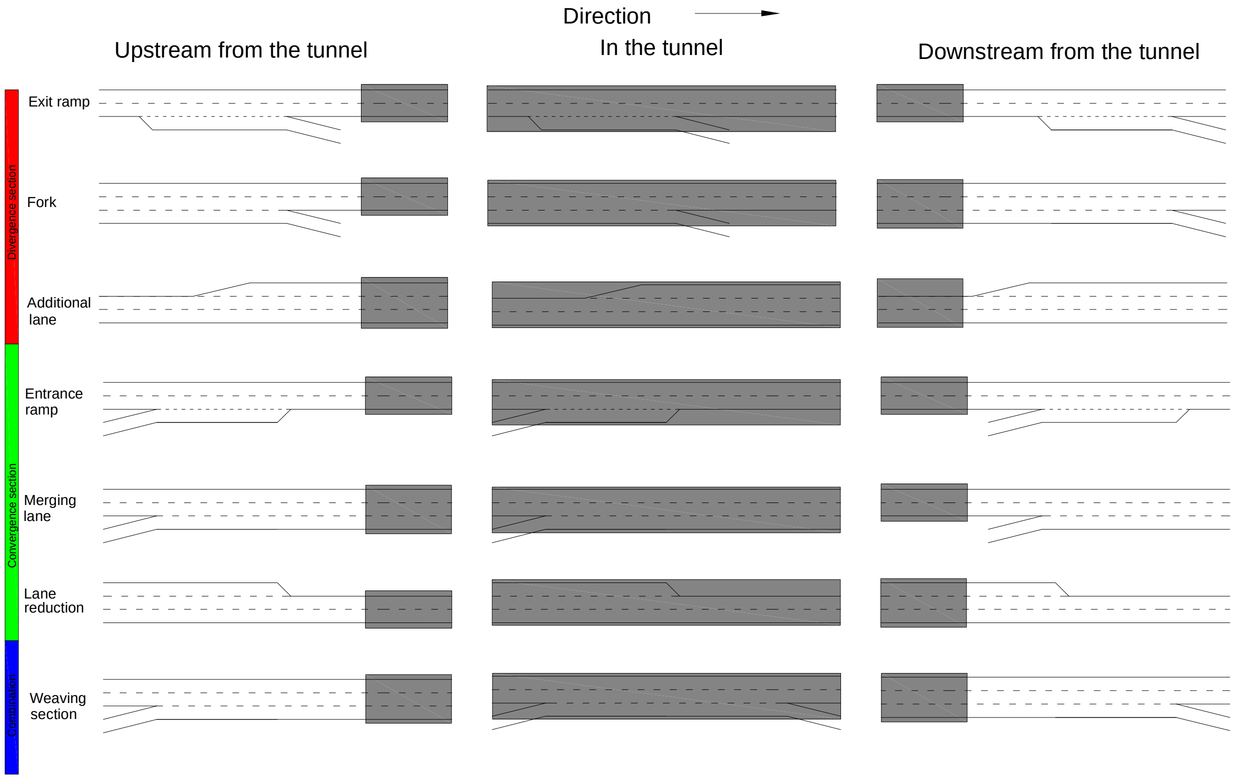

FIGURE 2 Possible combinations of convergence and divergence sections with a tunnel

The approach to this study is based on a comparison of situations on the 'open road' and in tunnels. The risks associated with both situations have been identified on the basis of descriptions of the driving task and traffic characteristics, requirements from road and tunnel guidelines and risk analyses (qualitative and quantitative). Both Dutch and international studies are used, with an emphasis on Dutch studies. Based on an analysis of the differences between an 'open road' and tunnels, the specific risks in and near tunnels have been determined.

The study also deals with risk compensating measures. If the level of safety in or near the tunnel is not acceptable, for example because it is not possible to position a convergence section far enough from the tunnel entrance, compensating measures must then be taken. Furthermore, additional measures must be taken if it is not possible to position a convergence or a divergence section outside the tunnel.

This study only considers tunnels in freeways: tunnels in urban roads are not considered. However, the approach used can be applied to these types of tunnels as well.

3. ACTUAL SITUATIONS

Existing tunnels in Dutch freeways

The current Dutch freeway network contains 13 tunnels. There are no tunnels with entrance or exit ramps within the tunnel. For most tunnels, the distance between the tunnel and the convergence or divergence section is still considerable. In case of the Drechttunnel, the Coentunnel, the Velsertunnel and the Zeeburgertunnel these points are positioned reasonably close to the tunnel entrance or exit: the distance is smaller than 600 m. The distance is smallest for the Thomassentunnel: there is a merging lane 120 m upstream of the tunnel and in the other direction there is an exit ramp 220 m downstream of the tunnel.

Planned tunnels

A number of new tunnels will be constructed in the Netherlands over the coming years:

- Entrance ramps and exit ramps inside the tunnel are planned for the Gaasperdammertunnel (A9);
- The Leidsche Rhine tunnel will be opened in 2010. An entrance and an exit ramp are located close to the tunnel.
- The plan for the double-level tunnel below Maastricht has recently been presented. Weaving sections for local traffic will be constructed in the upper tunnel tubes in both directions.

Tunnels in other European countries

Using aerial photos, a quick scan was carried out to identify tunnels in Belgium, France, Germany and Sweden:

- In Liège, Brussels and Antwerp in Belgium, there are a large number of tunnels with entrance and exit ramps located close to the tunnel. The distances between the tunnels and the beginning of the exit ramp or the end of the entrance ramp is often smaller than 300 m and in a number of cases it is even smaller than 100 m (for example, within the Liège E25 ring road).
- Such situations are prevalent around Paris within the Périphérique as well.
- In Germany near Hösbach, the A3 is covered over. At the location of the covering, the covered roadway connects to the A3 with an entrance and exit ramp.
- Stockholm in Sweden has a complete underground network of urban freeways: the Södra Länken. The Södra Länken consists of an underground system including a number of junctions. This underground road system includes all possible configurations: weaving sections, forks, merging lanes, entrance ramps and exit ramps (figure 1).

4. RESEARCH, RISK ANALYSES AND GUIDELINES

Based on research, risk analyses and guidelines related to the traffic safety of convergence and divergence sections and tunnels, risk theories have been defined for determining the minimum distances between a tunnel and a convergence or divergence section. This section summarises the key findings.

4.1 Are convergence and divergence sections near tunnels safe?

In 2004, the Civil Engineering Division of the Directorate-General for Transport, Public Works and Water Management carried out a study on the spacing between tunnels and the nearest junction and traffic safety (2). This study assessed the impact of convergence and divergence sections on the traffic safety of road sections in the Netherlands containing tunnels

The hypothesis put forward is that the accident rate increases more than proportionally as the distance between the convergence and divergence section and a tunnel decreases.

This hypothesis was tested on the basis of accident data, traffic intensity data and road section data derived from 11 motorway tunnels in the Netherlands over a period of 10 years (1992-2002). Figure 3 shows the results.

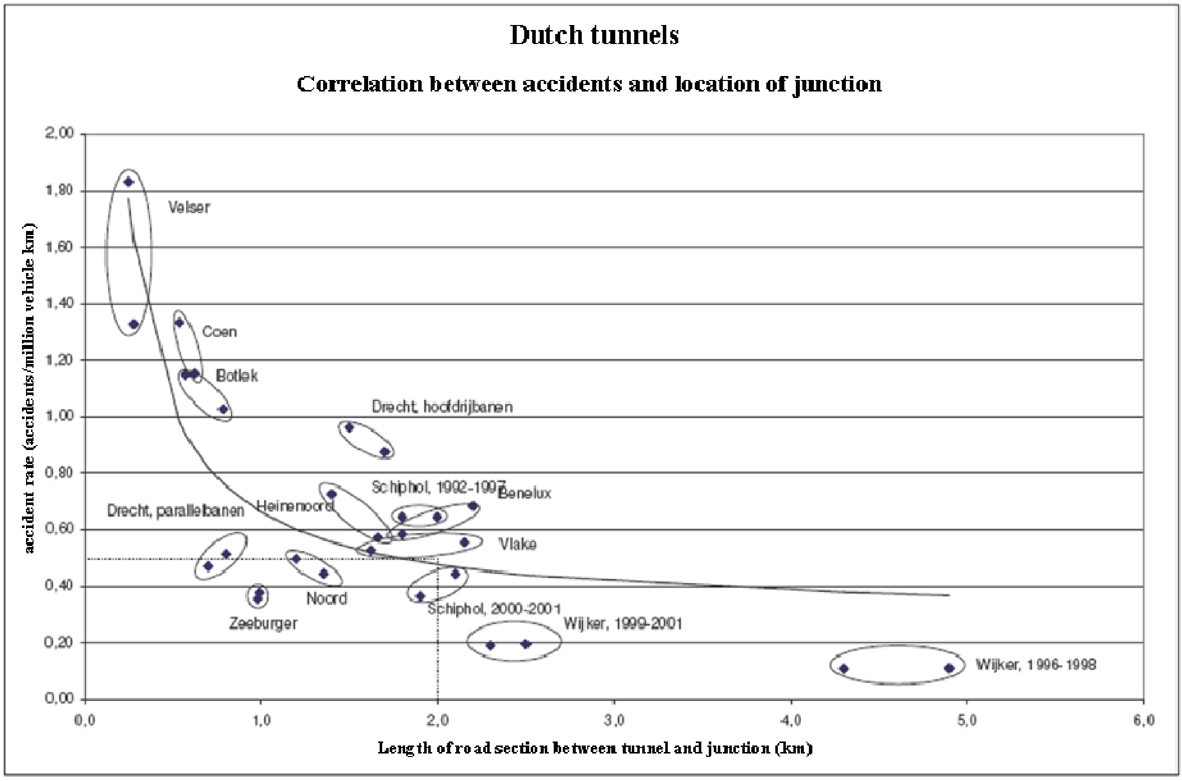

FIGURE 3 Relation between accident rates and the distance between a tunnel and the nearest junction

Based on this research, the hypothesis cannot be rejected: there is a relationship between the accident frequency and the distance between a tunnel and the next convergence or divergence section. Three areas were discovered that have an above-average accident rate:

- Convergence or divergence sections (primarily entrance ramps)
- The tunnel entrance
- The lowest point in the tunnel

Furthermore, accident peaks were discovered for a number of tunnels (particularly the Coentunnel and the Velsertunnel) where a convergence section and a tunnel entrance are in close proximity to each other. In fact, measures were taken for the Velsertunnel to reduce the number of accidents and to improve traffic flow.

Modifications to an exit ramp were also made during the reconstruction of the Schipholtunnel. In this case the exit ramp was relocated further downstream from the tunnel exit for the sake of traffic safety and the flow of traffic.

4.2 Austrian research

Under contract to the Austrian Bundesministerium für Verkehr, Innovation und Technologie *(Federal Ministry of Traffic, Innovation and Technology)*, tunnels with two-way traffic and one-way traffic were compared with other types of roads (3). The results of this analysis are based on data covering the period 1999-2003 for 136 Austrian tunnels, 110 of which have one-way traffic in each tunnel tube.

Figure 4 identifies the risk of accident, expressed in injury accident rate per million vehicle kilometres. The number of accidents is by far the highest at the level of the tunnel entrance. Just past the tunnel entrance the risk is relatively low. A detailed analysis of the cause shows that in the area of influence at the entrance and exit to the tunnel, the share of single-vehicle accidents is relatively high. The share of multiple-vehicle accidents is dominant within the tunnel.

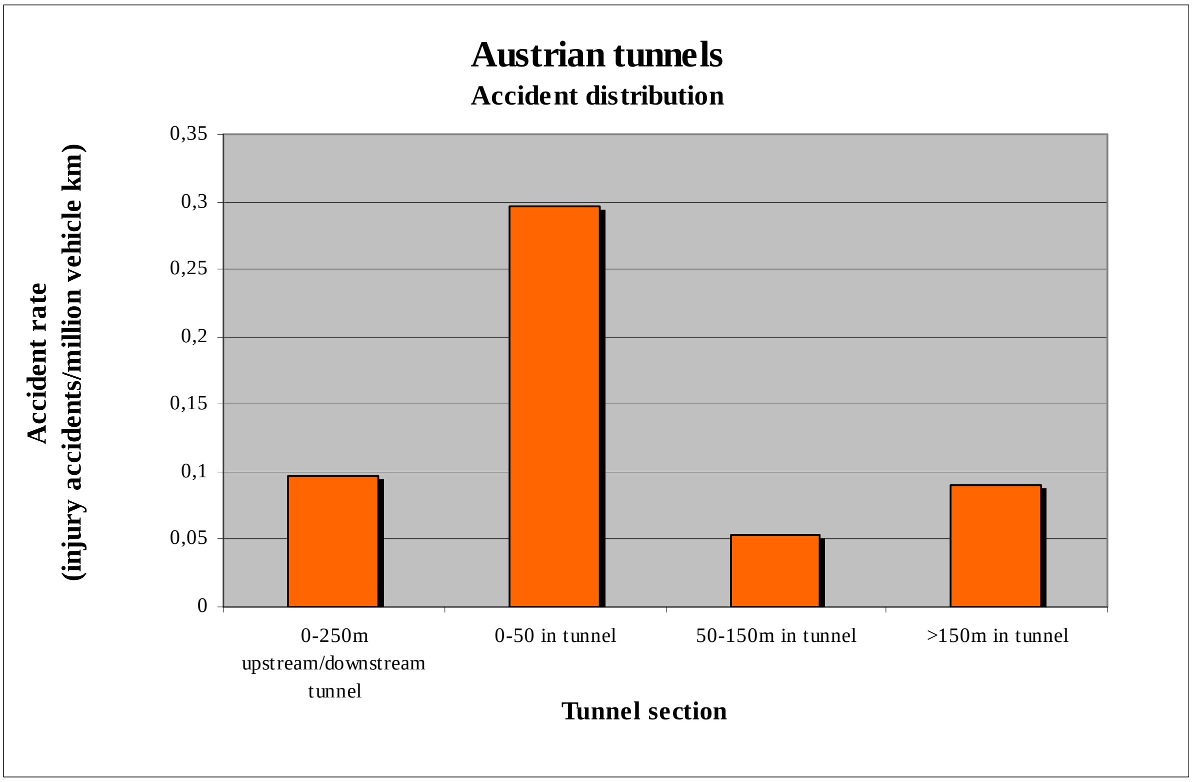

FIGURE 4 Distribution of (injury) accidents in Austrian tunnels

4.3 Guidelines for the geometric design of freeways

The limited capacity of drivers to take various decisions simultaneously or in rapid succession imposes conditions on the minimum distance that must be maintained between successive decision or action points.

The current Dutch guidelines for the geometric design of motorways, NOA (4), incorporate the turbulence distance concept. Turbulence distances are distances near convergence and divergence sections over which the driving behaviour and traffic flow are influenced as a result of these convergence and divergence section. Due to turbulence, the headways between vehicles and distribution of traffic over the lanes, change. The corresponding driving behaviour characteristics include accelerating, decelerating, and lane changes.

Table 2 shows the turbulence distances which should be used for determining the minimal distance between consecutive convergence and divergence sections.

TABLE 2 Turbulence distances

	Design Speed (km/h)		
Location of Road Section	**120**	**100**	**80**
Upstream from entrance ramp	150	130	100
Downstream from entrance ramp	750	600	500
Upstream from merging lane	150	120	100
Downstream from merging lane	375	300	250
Upstream from exit ramp	750	600	500
Downstream from exit ramp	150	120	100
Upstream from fork	150	120	100
Downstream from fork	150	120	100
Upstream from lane reduction	375	300	250
Downstream from lane reduction	150	120	100

In case of two consecutive convergence sections, the distances must be added together. In all other cases half of the sum of the two values can be used, because there is more traffic downstream a convergence section than there is upstream from a convergence section.

4.4 Tunnel Lighting

Driving through tunnels, road users are confronted by the following sequence of events (5):

- *Access zone*: During the approach to the tunnel, while still driving in daylight, the driver must be able to discern against the relatively dark entrance zone of the tunnel, whether the road is clear. During this process, the driver must be able to perceive sufficient contrasts. The access zone starts at a stopping distance from the entrance portal and ends at the entrance portal.
- *Entrance zone*: As the driver enters the tunnel, the quantity of perceived light is reduced considerably in a short period of time. This requires the eye to adapt to the changed lighting situation. Eye accommodation is a time-dependent process. The degree to which the lighting level in the further course of the entrance zone decreases must therefore be matched to the design speed. The length of the entrance zone is equal to the stopping distance.
- *Central zone*: When driving through the central zone of the tunnel, the driver has to adjust to the lower level of lighting. The lighting must be at a sufficient level and must be sufficiently uniform.
- *Exit zone*: As the driver approaches the exit he can be blinded by the exit, particularly in case of long tunnels (longer than approximately 1 km). In case of long tunnels where the lighting in the central zone is very low, an exit zone must therefore be created with an increased level of lighting. Tunnels for which the transit time is greater than 30 seconds must have an exit zone. The length of the exit zone must be at least equal to the stopping distance associated with the design speed plus 20 m.
- *Departing zone*: as the driver leaves the tunnel he must adjust to the daylight outside the tunnel. The departing zone is equal to the stopping distance.

In 1971/1972 in Japan, Narisada and Yoshikawa conducted research into the degree of concentration of drivers near tunnel entrances (6). They asked a number of test subjects to drive through more than 20 different tunnels. During this process they measured the eye movements, blinking and the time that the drivers kept their eye fixed on a specific point. Figure 5 shows the results.

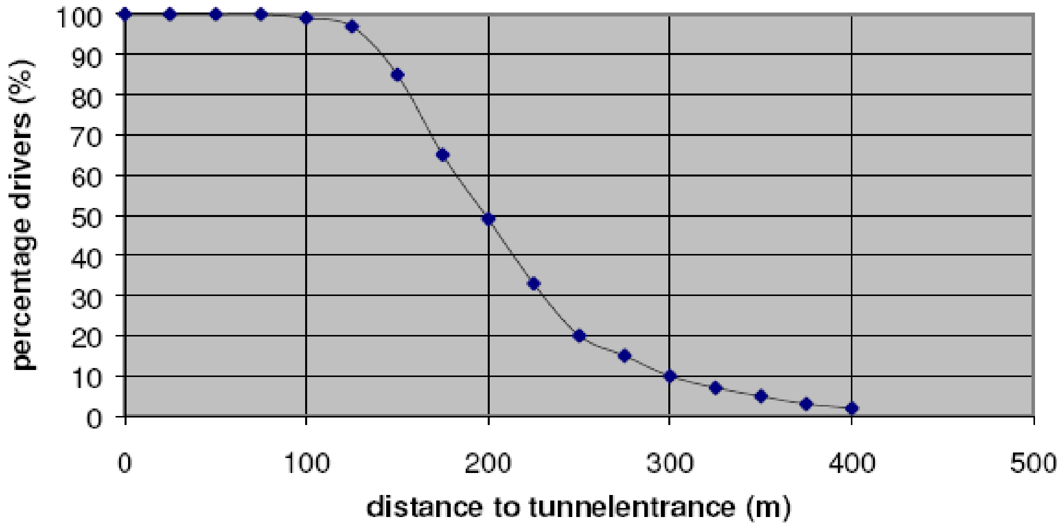

FIGURE 5 Fixation on the tunnel entrance as a function of the distance to the tunnel entrance

The horizontal axis represents the distance to the tunnel entrance. The vertical axis represents the percentage of drivers who are fixated on the tunnel entrance. This research does not specify whether the distances are dependent on speed. Since it is known that road users generally look further ahead as speed increases, this effect is also assumed to apply to tunnel entrances.

These results show that drivers begin to concentrate on the entrance of the tunnel, 200 to 300 m before the tunnel entrance and that at 100 m or less all drivers are fixated on the tunnel entrance. Remarkably, the surrounding traffic situation has barely impact on the distances.

Similar research was conducted in 1995/1996 in the Netherlands (7). The results are consistent with the Japanese research. Here too it was observed that drivers become fixated on the entrance portal within the 100–200 m zone before the entrance portal.

4.5 European Tunnel Directive and Netherlands Tunnel Act

The European Tunnel Directive (8) includes the following passage:

'With the exception of the emergency lane, the same number of lanes shall be maintained inside and outside the tunnel. Any change in the number of lanes shall occur at a sufficient distance in front of the tunnel portal; the distance shall be at least the distance covered in 10 seconds by a vehicle travelling at the speed limit. When geographic circumstances prevent this, additional and/or reinforced measures shall be taken to enhance safety.'

The Netherlands Tunnel Act, WARVW (9) and BARVW (10), includes the following provisions (translated from Dutch):

'The roadway leading up to a tunnel tube shall have the same number of lanes as the number of lanes in the tunnel tube. A reduction in the number of lanes leading up to the tunnel shall occur at such a distance from the tunnel that turbulent traffic movements within the tunnel, causes by the lane reduction, do not occur '

The following comment can be made to these requirements:

- The European Tunnel Directive and the Netherlands Tunnel Act are both unclear as to which type of convergence and divergence points are referred to.
- The Netherlands Tunnel Act does not explicitly identify the minimum distance between the reduction in the number of lanes and the tunnel entrance. While the European Tunnel

Directive does state this clearly, it does not clearly identify the reference points to which the 10 driving seconds apply.
- Configurations downstream of the tunnel that could cause turbulent traffic movements within the tunnel are not included.
- Convergence and divergence sections within the tunnel are not explicitly identified. For example, it is not clear whether entrance ramps within a tunnel are precluded.

5. MINIMUM DISTANCES

5.1 Introduction

From the research identified in section 4, it can be concluded that the tunnel entrance, tunnel exit and the convergence and divergence sections are discontinuities for the drivers; driving behaviour is influenced at these sections. From national and international research it can be deduced that a relatively large number of accidents occur near the entrance to the tunnel. From research in the Netherlands it can be concluded that the accident frequency increases the closer a convergence or divergence section is located to the tunnel entrance or exit.

There still are very few tunnels where convergence and divergence sections are located within the tunnel. Reliable accident data that permits the relationship between the presence of a convergence or divergence section and the accident frequency to be analysed, is therefore unavailable.
Since, due to its enclosed construction, the probability of injuries and casualties is greater in a tunnel than when an accident occurs outside a tunnel, the road designer must be reticent when it comes to including a convergence or a divergence section within a tunnel. Only when geographic and spatial factors make it impossible to locate a convergence or divergence section outside the tunnel, junctions within a tunnel may be considered. In such instances, supplementary safety measures are always needed to ensure that minimum safety levels can be maintained.

In this section the minimum distances between the different types of convergence and divergence sections and the tunnel entrance or exit are determined.

5.2 Risk theories

Through a combination of the concepts for turbulence, fixation and eye accommodation, the minimum distances between a convergence or divergence section and the tunnel entrance or exit can be determined. Table 3 shows these concepts and the corresponding distances:

TABLE 3 Theories and distances (design speed 120 km/h)

	Upstream	**Distance**	**Downstream**	**Distance**
Tunnel entrance	Fixation distance	400m	Entrance zone	210m
Tunnel exit	Exit zone	230m	Departing zone	210m
Convergence section	Turbulence	Various	Turbulence	Various
Divergence section	Turbulence	Various	Turbulence	Various

- As the fixation distance is longer than the length of the access zone, the fixation distance is used for the influence upstream of the tunnel entrance. The maximum distance at which drivers start to focus at the tunnel entrance, is used (400m).
- Table 3 shows the corresponding distances for a design speed of 120 km/h. For other design speeds, the distances are assumed to vary proportionally.
- The turbulence distances depend on the type of convergence or divergence section (see section 3.3).

These concepts are combined in three different risk theories, which are compared:

A. The area of influence of a convergence or divergence section and the area of influence of a tunnel entrance or exit are not allowed to overlap (X + Y).

B. The risk of the tunnel entrance or exit may not be increased due to the presence of a convergence or divergence section near the tunnel (max X,Y).
C. The minimum distance between a tunnel entrance or exit and a convergence or divergence section is equal to the sum of half of the two distances of influence. At half of the two distances of influence the risk is considered to be acceptable (1/2 X + 1/2 Y).

In figure 6 these theories are schematically illustrated for an entrance ramp upstream of a tunnel.

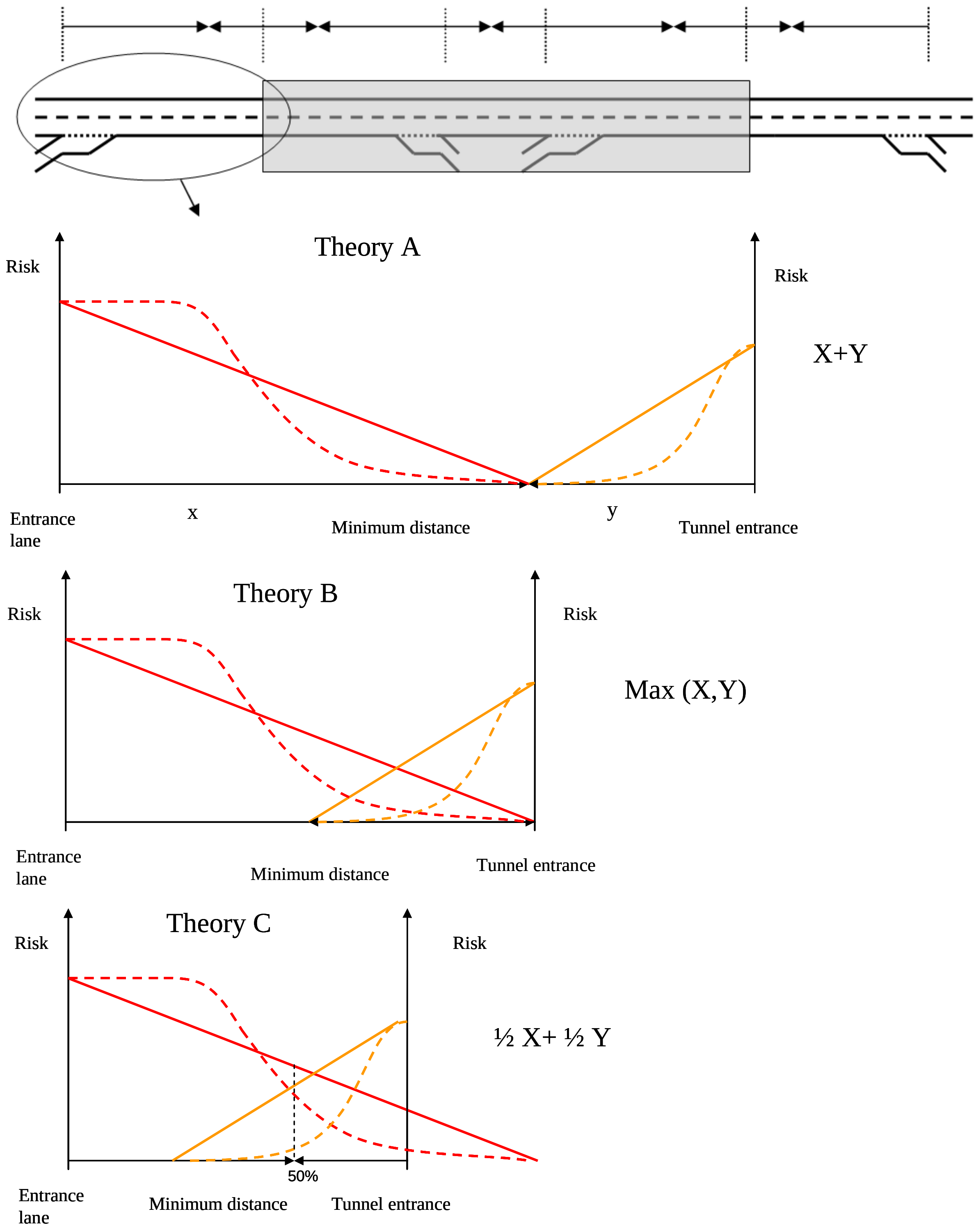

FIGURE 6 Risk theories illustrated for an entrance ramp upstream of a tunnel

On the horizontal axis the distance between the entrance ramp and the tunnel entrance is presented. The length X corresponds with the influence distance of the entrance ramp, the length Y with the influence distance of the tunnel entrance. The vertical axis shows the risk associated with the entrance ramp and the tunnel entrance.

The risk curve associated with the entrance ramp is indicated by the red lines, while the risk curve associated with the tunnel entrance is indicated by the orange lines. The magnitude of the risks is unknown. This study is primarily concerned with the distances over which risk is influenced. Because no studies are known that describe the risk curves associated with a convergence or divergence point or a tunnel entrance or exit, two possible risk curves are shown: a linear curve and an S-shaped curve.

Risk theory A is the most conservative approach, but is problematic in terms of its application in actual practice. In many situations it will be impossible to comply with this distance. Risk theories B and C are not very different. With theory C there is a slight, but acceptable increase in the additional risk. In a number of instances, theory B leads to greater minimum distances, while theory C leads to greater minimum distances in a number of other instances. Because theory B and C do not differ very much, the method resulting in the lowest distance was used to determine the minimum distance between a convergence or divergence section and a tunnel entrance or exit.

In case of tunnels with inclines (sunk tunnels) there is an additional risk associated with the downward sloping incline in comparison with tunnels without such inclines (land tunnels). This is why theory B is prescribed for this type of tunnels (no increased risk at the site of the tunnel entrance or exit).

Table 4 identifies the minimum distances.

TABLE 4 Minimum distances (m) between convergence and divergence sections and a tunnel entrance or exit

Type	Location	120 km/h	100 km/h	80 km/h
Exit Ramp	Upstream of the tunnel	275 (400)	230 (335)	185 (265)
	In the tunnel in relation to tunnel entrance	585	465	355
	In the tunnel in relation to tunnel exit	230	170	125
	Downstream of the tunnel	480	390	300
Fork	Upstream of the tunnel	275 (400)	230 (335)	185 (265)
	In the tunnel in relation to tunnel entrance	900	750	600
	In the tunnel in relation to tunnel exit	230	170	125
	Downstream of the tunnel	900	750	600
Entrance Ramp	Upstream of the tunnel	575 (750)	480 (625)	385 (500)
	In the tunnel in relation to tunnel entrance	210	150	105
	In the tunnel in relation to tunnel exit	605	485	375
	Downstream of the tunnel	180	140	100
Merging Lane	Upstream of the tunnel	375	315	250
	In the tunnel in relation to tunnel entrance	210	150	105
	In the tunnel in relation to tunnel exit	375	315	250
	Downstream of the tunnel	180	140	100
Lane reduction	Upstream of the tunnel	400	335	265
	In the tunnel in relation to tunnel entrance	-	-	-
	In the tunnel in relation to tunnel exit	-	-	-
	Downstream of the tunnel	295	230	180
Weaving section	Upstream of the tunnel	390	325	260
	In the tunnel in relation to tunnel entrance	210	150	105
	In the tunnel in relation to tunnel exit	230	170	125
	Downstream of the tunnel	180	140	100
Additional Lane	Upstream of the tunnel	200 (400)	165 (335)	135 (265)
	In the tunnel in relation to tunnel entrance	-	-	-
	In the tunnel in relation to tunnel exit	-	-	-
	Downstream of the tunnel	105	75	55

The minimum distances that apply to tunnels with inclines (sunk tunnels) are indicated in brackets.

6. COMPENSATING MEASURES

If it is not possible to comply with these minimum distances or if a convergence or divergence point is constructed within the tunnel, compensating measures must be implemented. The purpose of these measures is to compensate for the reduced level of safety.

Three categories of compensating measures can be identified: road design, dynamic traffic management and incident management. The following measures can be considered in these situations:

Road design

- Increase the distance to the tunnel, by changing the form of a junction (diamond instead of a cloverleaf junction)
- Reduction in the design speed
- Adding emergency lanes
- Separation of destinations prior to the tunnel

Dynamic traffic management

- Homogenisation of the traffic flow
- Keep your lane
- Overtaking prohibition for trucks
- Monitoring and maintaining safe following distances
- Ramp metering
- Dynamical close-off of entrance ramps and exit ramps (during peak periods)

Incident management

- Keep recovery vehicles standby
- Vehicle registration number tracking system
- Detection system for hazardous substances
- Incident assistance services

The measure that is the most effective will have to be determined for each individual situation. Measures that intervene as early as possible within the safety chain, prefer: measures that prevent accidents (preventative) are given preference over measures that influence the seriousness of the outcome of an accident (curative).

7. CONCLUSIONS AND RECOMMENDATIONS

Three theories were developed as part of this study that can be used to determine the required distance between a convergence or divergence section and a tunnel entrance or exit. The minimum distance between a convergence or divergence section and a tunnel entrance or exit is subsequently determined, arbitrary, by adopting the smallest distance determined on the basis of these three methods.

The Netherlands Tunnel Act (WARVW, BARVW) and the European Tunnel Directive are not clear with respect to the required minimum distance between a convergence or divergence section and the tunnel entrance or exit: it is not clear to which type of convergence and divergence section the requirements pertain, the reference points on which the minimum distances are based are not specified and the theory on which the requirements are based is unknown. To be able to unambiguously determine the minimum distances in actual practice, it is recommended that the requirements are made explicit and that the backgrounds on which the requirements are based will be identified. The results of this study can be used for this purpose.

The recommendations for the minimum distances are based on theories involving traffic flows at convergence and divergence sections and the impact of the tunnel entrance (and exit) on the driving behaviour of road users. These theories and the distances derived from these theories, should be validated on the basis of accident data. To obtain sufficient accident data, an international study is necessary.

The minimum distances are based on a combination of the influence distances of a convergence or divergence section and the tunnel entrance or exit. The lengths of the areas of influence are based on outdated research. New research into the relationship between driving behaviour and driving into and out of a tunnel can lead to a better rationalisation of the minimum distances or modification of these distances.

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