Road safety on motorways

Accident prediction models, accident modification factors and user manual for calculation tool

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Introduction

The Danish Road Directorate has asked Trafitec to develop tools to describe road safety for alternative road design and traffic management when planning new motorways or redesigning existing motorways. Trafitec authored the report "Uheldsmodeller, sikkerhedsfaktorer og værktøjer for strækninger – motorvejsnettet" (*Accident prediction models, accident modification factors and tools for segments – the motorway network),* which describes the road safety of motorways, including how accidents are modelled and how safety is affected by changes in road design and traffic management.

This publication is a short and easy-to-read version of the report mentioned above as well as a user manual to a calculation tool, which estimates expected numbers of accidents and injuries for motorway networks of various design and traffic management.

The publication describes the division of the motorway network into 15 different segment types. Accident prediction models have been developed for each type of segment, which can be used to estimate the expected numbers of accidents and injuries. The recommended accident prediction models are presented. For the five most common segment types a number of accident modification factors, which describe how safety is affected by changes in road design and traffic management, are also presented. The five segment types are motorway links, exit diverges, entrance merges, exit ramps and entrance ramps.

The recommended accident prediction models and accident modification factors are included in the calculation tool, which is available via Vejdirektoratet.dk and Trafitec.dk. The calculation tool user manual is the last chapter of this publication.

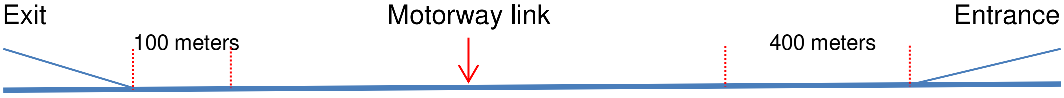
Division of motorway network

The motorway network is divided into 15 different segment types. Each type is presented below. To ensure the best estimation of a fair number of accidents and injuries for the segments, comments on how to divide or adjust specific segments are given.

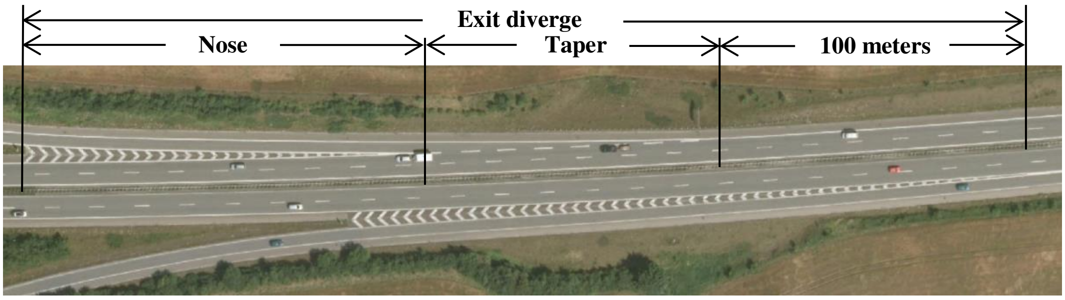
The five most common segment types

The five most common segment types are motorway links, exit ramps, entrance ramps, exit diverges and entrance merges. Safety performance functions (SPF) have been developed for the five segment types. A SPF describes the relationship between density of accidents and injuries on one hand and traffic volume on the other. Additionally, accident modification factors (AMF) have been developed. AMFs can be used to calculate changes in the number of accidents and injuries if the specific road design and traffic management on which the SPF is based upon is changed.

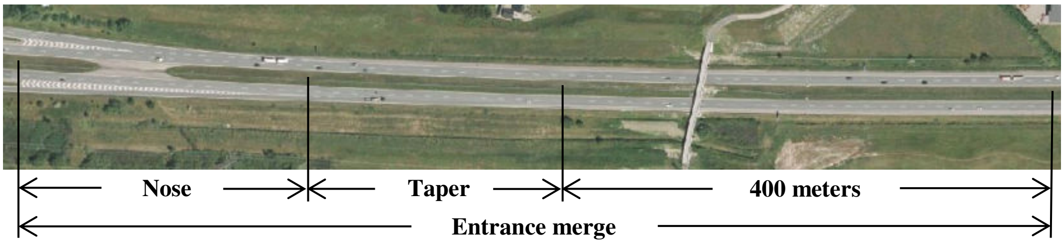
By motorway link is meant one side of the motorway, i.e. one direction of travel. On a motorway link there are no diverges and no merges. The minimum distance to the taper at entrance merges is 400 meters and 100 meters at exit diverges. There is at least 100 meters to the nose (ghost island) at a motorway diverge.



A motorway link is divided into sub-segments if the number of travel lanes is increased to 4 or reduced to 3. There should also be a division into sub-segments if travel lanes, hard shoulders or central reserve over a longer distance assume a different width. Division into sub-segments is unnecessary if the average travel lane has a width of 3.5 meters or more or the nearside hard shoulder has a width of 3.0 meters or more. Segments with more than two horizontal curves with radii below 4,000 meters should also be divided. There should also be a division where road lighting is started or ended. If the speed limit changes from 130 kph to a lower speed limit or vice versa, the segment should also be divided into sub-segments.



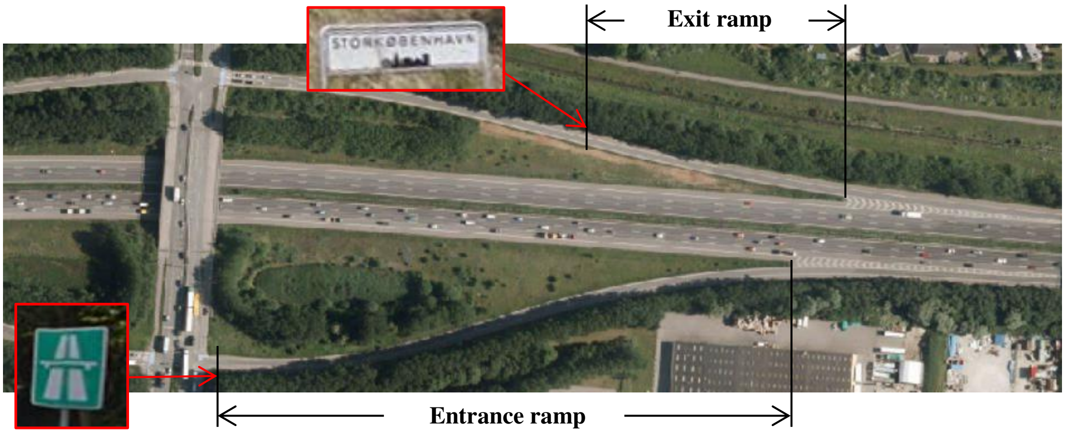
An exit diverge includes the nose (ghost island), the taper and the 100 meters of motorway before the taper. An exit diverge only includes one side of the motorway. The 100 meters of motorway before the taper is included in the exit diverge because there is an increased accident density on this section seen in relation to the motorway upstream.



An entrance merge includes the nose, the taper as well as the 400 meters of motorway after the taper. An entrance merge only includes one side of the motorway. The 400 meters of motorway after the taper is included in the entrance merge because there is an increased accident density on this section seen in relation to the motorway downstream.

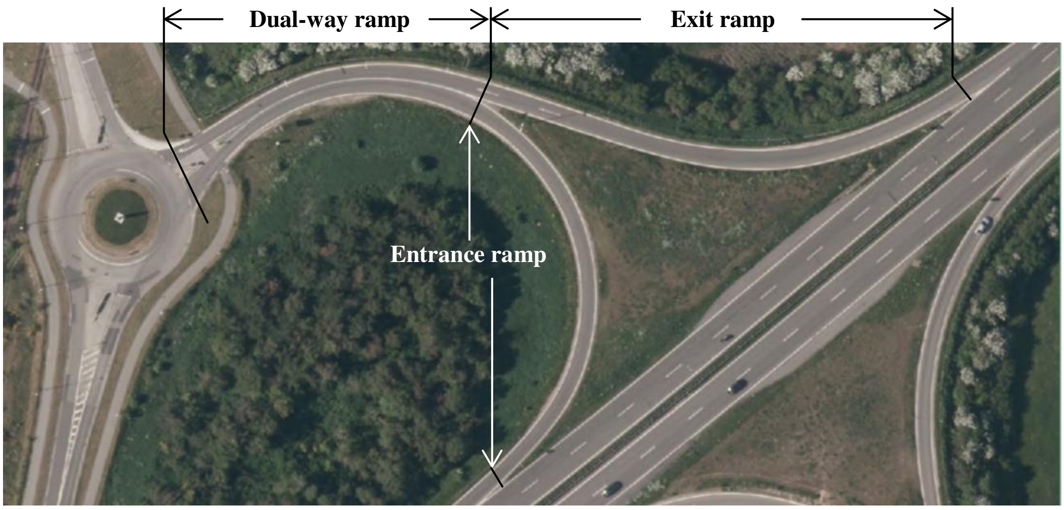
If there are less than 500 meters of motorway between tapers at respectively an entrance and an exit then the length of the entrance merge is reduced until the 100 meters of motorway before the exit taper is included in the exit diverge.

Neither exit diverges nor entrance merges must be divided in sub-segments. If the width of travel lanes, hard shoulders or central reserve varies along an exit diverge or entrance merge then the average width is used. If road lighting starts or ends on an exit diverge or entrance merge then the segment has road lighting. If the speed limit is changed from 130 kph to a lower speed limit or vice versa, the segment is indicated to have a speed limit of 130 kph.



An exit ramp goes from the back of the nose (e.g. end of exit diverge) till the ramp is no longer a part of the motorway network, e.g. town sign (urban zone), end of motorway sign, a yield- or stop line at a junction, or at the beginning of a ghost island where the exit ramp merges into another road, which is not a motorway. On an exit ramp there may be a diverge. If the two parts of ramps after the diverge does not have the same length, the average length is used for estimating accidents and injuries.

The entrance ramp begins at the motorway sign and ends at the back of the nose (e.g. start of entrance merge). At the entrance ramp there may be a merge. If the two parts of ramps before the merge does not have the same length, the average length is used for estimating accidents and injuries.

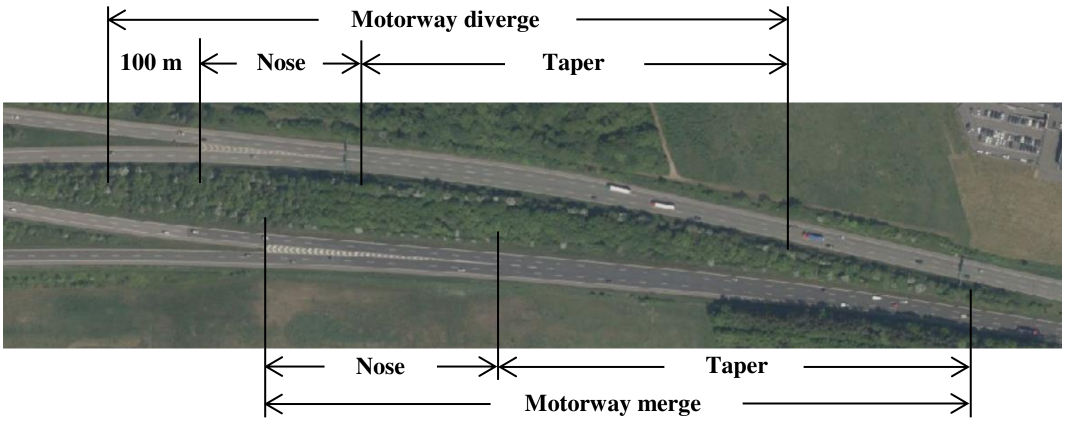


A special case is where an exit and entrance ramp merge together and form a road with traffic in both directions without a central reserve. This road is called a dual-way ramp if it is a part of the motorway network. On a dual-way ramp, both directions of traffic are considered as part of the motorway network, even though one direction of traffic is only partially or not part of the motorway network. In this special case, the exit ramp ends and entrance ramp starts at the end of the dual-way ramp. A dual-way ramp is not one of the five most common segment types, but is one of several other ramps.

Exit and entrance ramps must not be divided into sub-segments. If widths of lanes or hard shoulders varies on the ramp then the average width is used. If road lighting starts or ends on the ramp then the ramp is considered having road lighting. If there are more than two horizontal curves with radii less than 1,000 meters only the two curves with the lowest radii are included in the estimation of accidents and injuries.

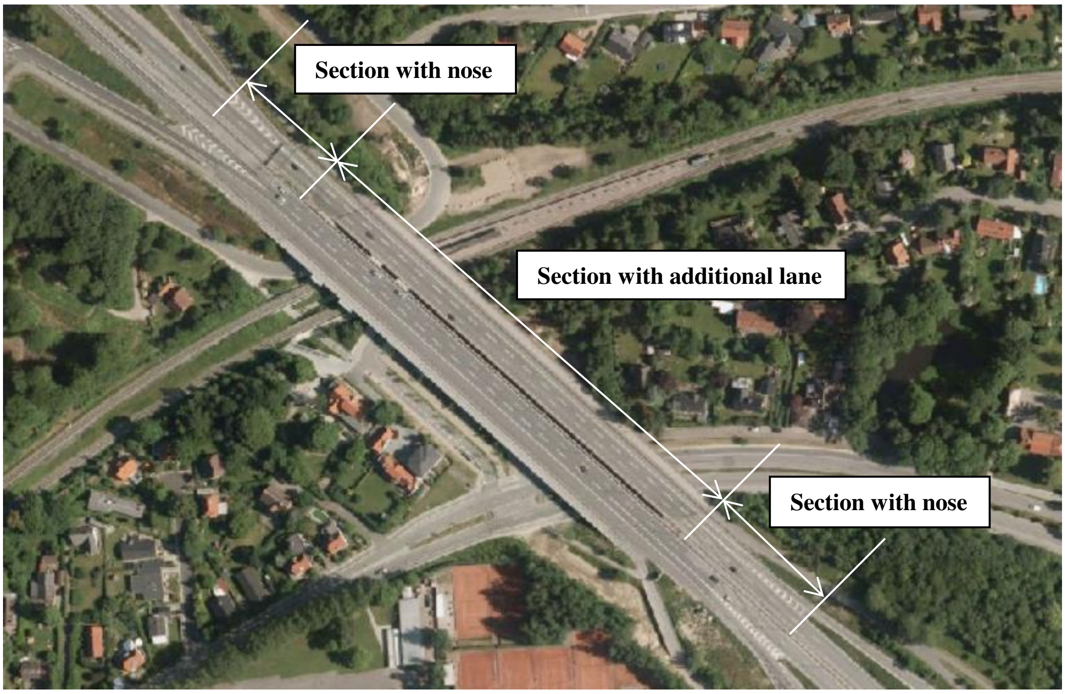
Other segment types

For the ten other segment types accident prediction models have been developed that for varying design and traffic management describe relationships between density of accidents and injuries on the one hand and traffic volume on the other. No accident modification factors have been developed for other segment types.



The motorway is divided into two motorways in a motorway diverge. The motorway diverge only includes one side of the motorway. A motorway diverge may include a taper section with lane gain, and always includes a nose as well as the first 100 meters of the two motorways after the back of the nose. The two times of 100 meters of motorway after the back of the nose are included in the motorway diverge because there is an increased accident density on this section seen in relation to the motorways downstream.

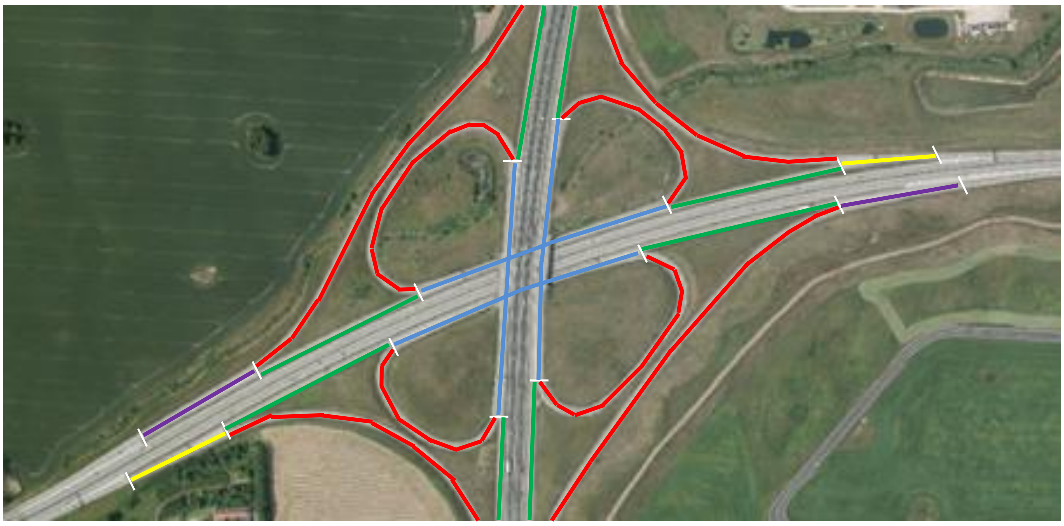
Two motorways merge together to one in a motorway merge. The motorway merge only includes one side of the motorway. The motorway merge includes the section with the nose and perhaps a taper section where there is lane drop.



A motorway weaving segment, see figure above, is an entrance merge with a lane gain followed by an exit diverge with a lane drop. There is thus an additional lane on the section between the entrance and exit compared to the motorway before and after the motorway weaving segment. The motorway weaving segment is only one side of the motorway.

A service area is usually a rest area with or without a service station. In a few cases, the service area consists of/includes a bus stop. The service area is most often connected directly to the motorway by an exit diverge and an entrance merge. In a few cases the service area is connected to exit and entrance ramps with respectively a ramp diverge and a ramp merge at each end of the service area. The length of the service area is based on the mile markers on the adjacent motorway link.

In addition to the before mentioned dual-way ramps there are five other types of ramps. These five other ramps are usually located in motorway junctions (interchange of two motorways).



A direct connector ramp (red lines in the above figure) connects one motorway to another motorway in a motorway junction. A direct connector ramp must have only one travel lane on a part of the segment. If the direct connector ramp has two or more travel lanes all the way it must be regarded as a motorway link. A parallel ramp (green lines in the above figure) is a ramp with one lane, which runs parallel to the motorway.

In a ramp diverge (yellow lines in the above figure) a ramp is divided into two ramps. A ramp diverge consists of a taper and a nose. In motorway junctions ramp diverges are often situated right after an exit diverge. Where ramp diverge and exit diverge overlap each other the length of the ramp diverge is reduced, so the ramp diverge begins at the back of the nose of the exit diverge.

In a ramp merge (purple lines in the above figure) two ramps runs together to one ramp. A ramp merge consists of a nose and a taper section. In motorway junctions the ramp merge is often situated just before an entrance merge. Where ramp merge and entrance merge overlap each other the length of the ramp merge is reduced, so it ends at the back of the nose of the entrance merge.

A ramp weaving segment (blue lines in the above figure) is a ramp merge with a lane gain followed by ramp diverge with a lane drop. Thus, there is an additional lane between the merge and the diverge seen in relation to the parallel ramps before and after the ramp weaving segment.

Accident prediction models

Safety performance functions (SPF) have been estimated for five specific variants of motorway links, exit diverges, entrance merges, exit ramps and entrance ramps. SPFs can estimate expected numbers of accidents and injuries for those variants. SPFs apply to segments with the following road design, road furniture and traffic management:

Road design, road furniture and traffic management	Motorway link	Exit diverge	Entrance merge	Exit ramp	Entrance ramp
Width of nearside hard shoulder	≥ 3.0 m	≥ 3.0 m	≥ 3.0 m	≥ 0.5 m	≥ 0.5 m
Number of travel lanes	2	2	2	1	1
Width of travel lane	≥ 3.5 m	≥ 3.5 m	≥ 3.5 m	≥ 3.5 m	≥ 3.5 m
Lane drop / lane gain	No	No	No	-	-
Diverge / merge	-	-	-	No	No
Width of offside hard shoulder	0.5 m	0.5 m	0.5 m	0.5 m	0.5 m
Width of central reserve	5.5 m	4.9 m	4.9 m	-	-
Curves / curve radius	≥ 4,000 m*	≥ 4,000 m*	≥ 4,000 m*	Straight diamond	Straight diamond
Safety barrier in central reserve	Semi-rigid steel	Semi-rigid steel	Semi-rigid steel	-	-
Curve marking	No	No	No	Yes/No	Yes/No
Road lighting	No	No	No	No	No
Glare screen	No	No	No	-	-
Tunnel	No	No	No	No	No
Speed limit kph	130	130	130	110-130	110-130
Recommended speed	No	No	No	Yes/No	Yes/No
Hard shoulder running	No	No	No	No	No
Variable message signs	No	No	No	No	No
Ramp metering	-	-	No	-	No

Note: ”-” = not relevant, ”” = estimated.*

SPFs for motorway links, exit diverges, entrance merges and entrance ramps have the following function expression:

$$\mathrm{UHT} = \mathrm{a} \cdot \mathrm{N}^{\mathrm{p}} \qquad (1)$$

where UHT is the accident or injury density per km per year, a and p are estimated constants and N is the annual average daily traffic (AADT). By multiplying L (segment length in km) on the right-hand side of function 1 you get U (number of accidents or injuries per year) on the segment ($\mathrm{U} = \mathrm{a} \cdot \mathrm{L} \cdot \mathrm{N}^{\mathrm{p}}$).

For exit ramps the function expression of the SPF is slightly different:

$\text{UHT} = \text{a} \cdot \text{N}^{\text{p}} \cdot e^{\text{b}_1 \cdot \ln(\text{L})}$ (2)

where UHT is the density of accidents per km per year, a, b_1 and p are estimated constants, L is the length of the ramp in km and N is AADT on the ramp. By multiplying L on the right-hand side of function 2 you get U (number of accidents per year) on the ramp ($\text{U} = \text{a} \cdot \text{L} \cdot \text{N}^{\text{p}} \cdot e^{\text{b}_1 \cdot \ln(\text{L})}$).

Accident prediction models have been estimated for motorway diverge, motorway merge, motorway weaving, service area, dual-way ramp, direct connector ramp, parallel ramp, ramp diverge, ramp merge and ramp weaving segments. These models can be used to estimate expected numbers of accidents and injuries for each segment type, but for an unknown road design and traffic management, since these models are not based on specific variants.

Accident prediction models for motorway diverges, motorway merges, motorway weavings and service areas have the following function expression:

$\text{UHT} = \text{a} \cdot \text{N}^{\text{p}}$ (3)

where UHT is the density of accidents per km per year, a and p are estimated constants and N is AADT. By multiplying L (segment length in km) on the right-hand side of function 3 you get U (number of accidents per year) on the segment ($\text{U} = \text{a} \cdot \text{L} \cdot \text{N}^{\text{p}}$).

Accident prediction models for dual-way ramps, direct connector ramps, parallel ramps, ramp diverges, ramp merges and ramp weaving segments have the following function expression:

$\text{UHT} = \text{a} \cdot \text{bx} \cdot \text{N}^{\text{p}}$ (4)

where UHT is the density of accidents per km per year, a, b and p are estimated constants, x is type of ramp and N is AADT. By multiplying L (length of ramp in km) on the right-hand side of the function 4 you get U (number of accidents per year) on the ramp ($\text{U} = \text{a} \cdot \text{bx} \cdot \text{L} \cdot \text{N}^{\text{p}}$).

The recommended safety performance functions and accident prediction models with estimated constants are presented in appendix 1. All models are calibrated to apply to Denmark. Calibration accounts for varying degree of underreporting in police districts. The calibration therefore enables reasonable use of unit prices for accident costs with realistic accident cost results. The unit prices are set for 2012 price level by DTU Transport, and are DKK 18,609,867 per killed, 3,188,341 kr. per severe injury, 480,261 kr. per slight injury and 697,929 kr. in property damage per reported accident. The unit price for property damage apply both to injury accidents and property-damage-only accidents with police report (PDO accident w/report). Property-damage-only accidents without police report (PDO accident no report) are not valued, and therefore do not have a unit price.

Appendix 1 shows that the SPFs dispersion parameter is close to zero, especially for accident prediction. This is an indication that the extent of unexplained systematic variation in accident occurrence is modest. Traffic volumes often explains more than 80 % of the systematic variation in SPFs. The estimated constants for AADT are close being true relationships and can be considered being causal. The SPFs explain 39-95 % of the systematic variation in accident occurrence, while the accident prediction models only explain 24-43 %. SPFs only explain 26-32 % of the systematic variation in injury occurrence. This is because variables related to people and vehicles such as age, seat belt and vehicle type are not included in the models.

Only in a few cases, the recommended SPFs and accident prediction models for a segment type are able to estimate the number of accidents and injuries divided into the various accident and injury severities. However, using conversion factors, the models may be used to estimate the number of injury accidents, PDO accidents w/report and PDO accidents no report respectively as well as the number of killed, severe injuries and slight injuries respectively. These conversion factors are described in appendix 2.

The estimated number of accidents and injuries per year apply for the period 1999-2012 for ramps and for the years 2005-2012 for other segments, i.e. motorways and service areas. Using estimated year factors it is possible to convert the number of accidents and injuries per year e.g. from the period 2005-2012 to a single year e.g. 2006 or 2010 or another period of years e.g. 2009-2012. The year factors are described in appendix 3.

SPFs and accident prediction models together with the described conversion and year factors are an integrated part of the calculation tool. A user manual for the calculation tool is given later in this publication. The tool may estimate the expected number of accidents and injuries and accident costs for one year or a multiple-year period just by entering AADT, segment type and length into the tool.

Accident modification factors

Accident modification factors (AMF) are linked to and can be used in relation to developed safety performance functions (SPF). By using SPFs in combination with AMFs an expected number of accidents and injuries can be estimated for a large proportion of the existing motorway network with the current variation in road design and traffic management. They can also be used to estimate the expected number of accidents and injuries for motorway networks with alternative road designs and traffic management in connection with planning and design of new motorways and motorway redesigns.

The AMFs are linked to the following design conditions and SPFs:

AMF / Type of design	Motorway link	Exit diverge	Entrance merge	Exit ramp	Entrance ramp
Number of travel lanes	X	X	X		
Width of travel lane	X	X	X	X	X
Hard shoulder running	X				
Width of nearside hard shoulder	X	X	X		
Width of offside hard shoulder	X	X	X	X	X
Width of central reserve	X	X	X		
Radii of horizontal curves	X	X	X	X	X
Road lighting	X	X	X	X	X
Tunnel	X	X	X	X	X
Service area	X				
Lane drop and lane gain	X	X	X		
Interchange ramp design				X	X
Curve marking	X	X	X		
Speed limit	X	X	X		
Ramp metering			X		

It has been attempted to set up additional AMFs for e.g. safety barriers in central reserve and on right-hand side of the nearside hard shoulder, vertical curves, gradients, safety zones, glare screens, chevron markings and overtaking restrictions. AMFs for these measures have not been set up because safety effects related to some of measures are very uncertain, while data about other measures have not been provided for the segments that SPFs are based upon.

AMFs are described in the following. An AMF and a result from a SPF is multiplied and this changes the expected number of accidents and injuries to that you would expect for the chosen design given by the setting of the AMF. It is possible to account for special cases regarding AMFs in the calculation tool.

Number of travel lanes

Foreign before-after evaluations of motorway widening from 2 to 3 through going travel lanes in each direction of travel show that such widenings do not affect the number of accidents and injuries significantly. Similarly, results from Danish and foreign accident prediction models indicate no difference in safety on motorway links, exit diverges and entrance merges with respectively 2 and 3 lanes in one travel direction.

AMF for number of travel lanes	Number of travel lanes			
	2 lanes	3 lanes	4 lanes	5+ lanes
Accidents and injuries	1.00	1.00	1.20	1.20

Accident modification factors for number of travel lanes on motorway links, exit diverges and entrance merges (one side of motorway, i.e. one travel direction).

Foreign before-after evaluations of motorway widenings to 5 and 6 lanes in each travel direction show an increase in accident and injury numbers by approx. 10 %. Some foreign and Danish studies indicate that widenings from 3 to 4 lanes increase the number of accidents and injuries by 40-50 %, while other foreign studies indicate a slight decrease when widening to 4-5 lanes. The AMFs used for the number of travel lanes are thus a reasonable average of the study results.

In the case of very wide motorways, a safety barrier between travel lanes of the same direction of travel, e.g. 3+2 or 3+3 lanes in the same travel direction, is sometimes used abroad. It is possible that such separation of lanes eliminates or reduces the increase in accidents and injuries most commonly occurring when widening to 4, 5 or 6 lanes in one travel direction.

Width of travel lane

Foreign studies show that a reduction in the width of a travel lane on motorways by 0.25 meters increases the number of accidents and injuries by approx. 3 %, whereas on ramps the increases are about 5 %. Danish studies contain too few motorways and ramps with narrow lanes to document these relations, but clearly indicate that travel lanes wider than 3.5 meters have the same safety as 3.5 meters wide travel lanes. The following AMF are used for average lane width:

AMF for average width of travel lane	Width of travel lane (meters)			
	2.75	3.00	3.25	3.50 or more
Accidents and injuries – Motorways	1.09	1.06	1.03	1.00
Accidents and injuries – Ramps	1.12	1.08	1.04	1.00

Accident modification factors for average lane width on motorway links, exit diverges, entrance merges as well as exit and entrance ramps.

Hard shoulder running

A number of European before-after evaluations show that the use of emergency lane as an extra travel lane at high traffic volumes (hard shoulder running) reduces the number of accidents by approx. 20-30 % and the number of injuries by about 40-55 % in periods when hard shoulder running is active. Some American studies explain that these reductions may occur because the accident rate increases significantly when the number of vehicles per lane per hour exceeds about 1,250. It is estimated that hard shoulder running on motorways is a safety benefit at volumes higher than 1,350-1,400 vehicles per lane per hour and the safety benefit is getting smaller as the number of travel lanes increases. The safety effects of hard shoulder running on diverge and merge segments are unknown.

AMF for hard shoulder running	Number of travel lanes on motorway link			
	2 lanes	3 lanes	4 lanes	5+ lanes
Injury accidents and injuries	0.60	0.70	0.76	0.80
PDO accidents	0.80	0.85	0.88	0.90

Accident modification factors for hard shoulder running on motorway links with more than 1,350-1,400 vehicles per lane per hour. The AMFs are only valid when hard shoulder running is active.

Width of nearside hard shoulder

Foreign before-after evaluations show that construction of wide nearside hard shoulders (emergency lanes) reduces the number of injury accidents by approx. 19 %, while the reduction in PDO accidents is significantly greater. The Danish studies show exactly the same, but also shows that hard shoulders wider than 3 meters provide the same level of safety as hard shoulders of 3.0 meters. The AMFs below are solely based on Danish studies.

AMF for width of nearside hard shoulder	Width of nearside hard shoulder (meter)						
	0.0	0.5	1.0	1.5	2.0	2.5	3.0 and wider
Injury accidents and injuries	1.28	1.23	1.19	1.14	1.09	1.05	1.00
PDO accidents	1.59	1.49	1.39	1.30	1.20	1.10	1.00

Accident modification factors for width of nearside hard shoulder on motorway links, exit diverges and entrance merges.

Both Danish and foreign studies show that the width of nearside hard shoulders on ramps affect safety. However, it has not been possible to estimate SPFs for ramps where the width of the nearside hard shoulder is maintained at a fixed level. When SPFs for exit and entrance ramps was developed, the average width of nearside hard shoulders was 2.4 meters. Therefore, by using SPFs for these ramps, the number of accidents and injuries will be slightly overestimated if the nearside hard shoulder is wider than 2.4 meters and underestimated if it is narrower than 2.4 meters.

Width of offside hard shoulder

In Denmark, the width of the offside hard shoulder (next to the central reserve) is almost always 0.5 meters wide. It has therefore not been possible to estimate a safety effect related to the width of the offside hard shoulder based on Danish data. Abroad, it has been found that the number of accidents and injuries decrease about 4 % on motorways for each meter the offside hard shoulder is widened, while the reduction is about 8 % on ramps. It is presumed that offside hard shoulders of 3.0 meters provide the same safety in Denmark as wider offside hard shoulders. The following AMFs are used for offside hard shoulders:

AMF for width of offside hard shoulder	Width of offside hard shoulder (meters)						
	0.0	0.5	1.0	1.5	2.0	2.5	3.0 and wider
Accidents and injuries on motorways	1.02	1.00	0.98	0.96	0.94	0.92	0.90
Accidents and injuries on ramps	1.04	1.00	0.96	0.92	0.88	0.84	0.80

Accident modification factors for width of offside hard shoulder on motorway links, exit diverges and entrance merges as well as exit and entrance ramps.

Width of central reserve

Foreign studies indicate that the number of accidents is reduced by about 1 % when the width of the central reserve is widened by 1 meter, while the number of injuries decreases by only approx. 0.3 %. Danish studies indicate that the number of accidents is reduced by about 0.7 %, while the number of injuries increases by approx. 0.2 % when the width of the central reserve is widened by 1 meter. The following AMFs are used for the width of the central reserve:

AMF for width of central reserve	Width of central reserve (meter)					
	2.0	3.0	4.0	5.0	8.0	11.0
PDO accidents	1.03	1.02	1.01	1.00	0.97	0.94

Accident modification factors for width of central reserve on motorway links, exit diverges and entrance merges.

Radii of horizontal curves

Many studies show that the numbers of accidents and injuries decrease as the radii of horizontal curves increase. Studies also show that horizontal alignment affects the accident rate more on narrow roads than on wide roads (at the same speed) and therefore the curve radii is off less importance for motorways than on e.g. trunk roads in rural areas. The AMFs are based on an American model for horizontal curve radius on motorways, which is consistent with other studies of curve radius on motorways. The model indicates that the AMF for horizontal curves on motorways equals $e^{0.1096 \cdot CD}$, where CD = 1,746.5 / curve radius in meters. This model is valid for curves with radius of 300 meters or more. It is estimated that motorways included in the Danish SPFs have a level of safety equivalent to a horizontal radius of 4,000 meters, so the AMF used equals $e^{0.1096 \cdot CD} / e^{0.1096 \cdot 1{,}746.5/4{,}000}$. The following AMFs apply to horizontal curves on Danish motorways:

AMF for horizontal curves	Radius on horizontal curve (meters)							
	300	500	800	1,000	1,500	2,000	3,000	≥ 4,000
Accidents and injuries	1.80	1.40	1.21	1.15	1.08	1.05	1.02	1.00

Accident modification factors for horizontal curves on motorway links, entrance merges and exit diverges.

Curves on ramps also affect road safety. Studies show that the average vehicle speed at the beginning of the curve on the ramp is of great importance for how much the curve affects safety. The AMF for horizontal curve radius on ramps is based on an American model, solely based on motorway ramps, which results are similar to other studies of curves. The model for AMFs for curves on entrance and exit ramps is:

$$\text{AMF} = 1 + a \cdot \frac{1{,}000}{32.2} \cdot \left[\sum_{i=1}^{n} \left(\frac{V_{ent,i}}{R_i} \right)^2 \cdot P_{c,i} \right]$$

where a is a constant (1.545 for injury accidents and 1.961 for PDO accidents), $V_{ent,i}$ is the average speed (feet / second) at the beginning of curve i, R_i is the radius of curve i in feet and $P_{c,i}$ is the curve length / ramp length. Only curves on the part of the ramp, which is a part of the motorway network and have a radius of less than 1,000 meters, can be included. Curves on junction corners at ramp junctions are not to be included. SPFs for exit and entrance ramps are based on straight diamond ramps.

Curve marking

Some studies show that curve marking reduce the number of accidents in curves. Curve marking can be e.g. warning signs, recommended speed, chevrons, painting of safety barrier and sequential flashing beacons. However, studies of curve marking on motorways are few, but show that curve marking only affects the number of accidents in sharp curves. There is no basis for setting AMFs for curve marking on ramps. The following AMFs are used for curve marking on motorways:

AMF for curve marking	Radius 0-300 meters	Radius 301-600 meters	No curve marking
Injury accidents and injuries	0.50	0.75	1.00
PDO accidents	0.60	0.80	1.00

Accident modification factors for curve marking for curves with a radius between 0-300 meters and 301-600 meters respectively on motorway links, exit diverges and entrance merges. Curve marking include warning sign, recommended speed and chevrons.

Road lighting

Several studies show that road lighting on motorways and ramps results in a decrease in accidents and injuries in darkness between 5 and 58 %. Danish studies show that road lighting on motorways is of great importance for the number of accidents and injuries. The share of accidents that occur in darkness on motorways and ramps in Denmark have been taken into account setting up the following AMFs for road lighting:

AMF for road lighting	Accidents			Injuries		
	Injury	PDO w/report	PDO no report	Killed	Severe	Slight
With road lighting	0.95	0.95	0.96	0.79	0.94	0.97
Without road lighting	1.00	1.00	1.00	1.00	1.00	1.00

Accident modification factors for road lighting on motorway links, exit diverges, entrance merges as well as exit and entrance ramps.

Tunnel, service area, lane drop and lane gain

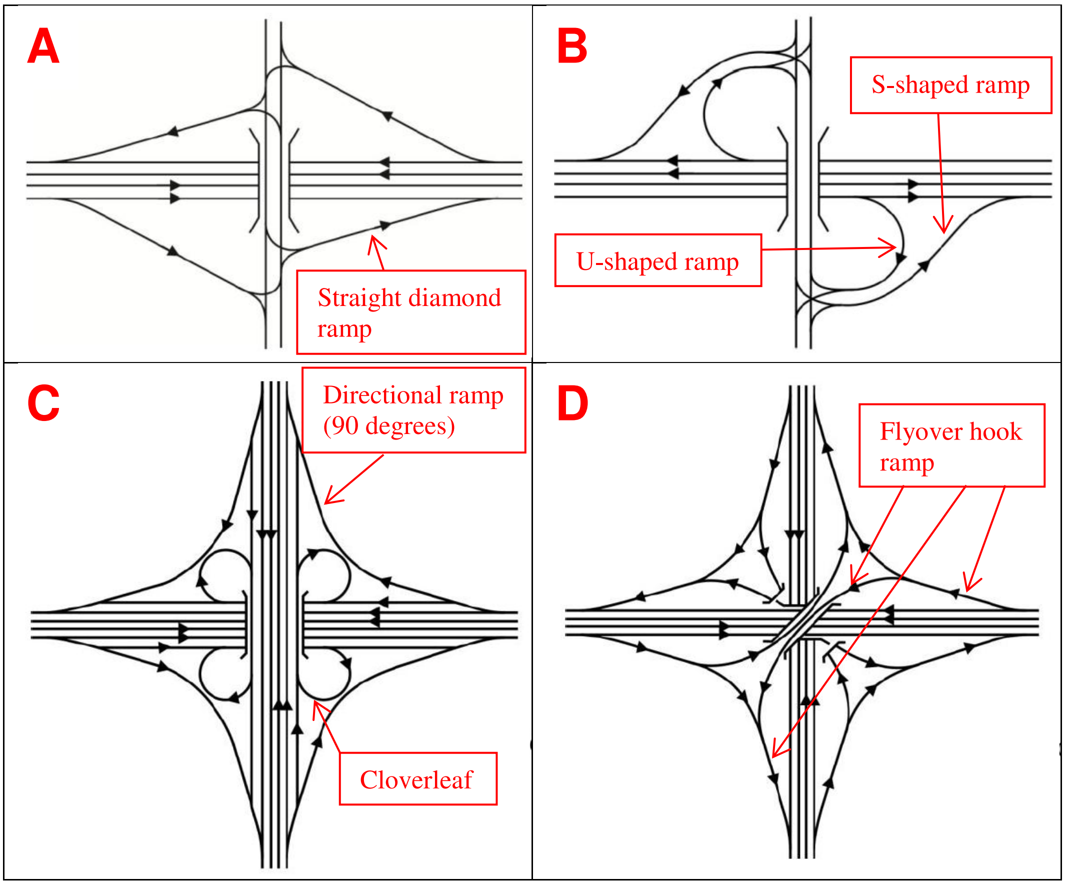
Foreign studies show the accident rate in motorway tunnels is approximately the same as the accident rate on comparable motorways (not in tunnel). The Danish studies, however, show that the accident and injury rate in tunnels is far higher than on other motorways, but this is without accounting for vertical curves, gradients and accident underreporting. AMFs for motorways and ramps in tunnel and not in tunnel are both set to 1.00, i.e. no safety difference.

Two foreign studies indicate that the number of accidents on motorways downstream service areas is lower than before service areas. Danish studies show the opposite meaning that the number of accidents on motorways after service areas is 5 % higher than before service areas. AMFs for motorway links are set to 1.00 both before and after service areas, i.e. no safety difference.

The Danish studies shows that motorway links, exit diverges and entrance merges with lane drop or lane gain do not have a higher accident rate than comparable segments without lane drop or gain. AMFs for lane drop / lane gain is set to 1.00, i.e. no safety difference, for motorway links, exit diverges and entrance meges.

Interchange ramp design

Ramps on the motorway network can be designed in a variety of ways. The figure on the next page shows some common interchange ramp designs.



Four types of grade separated junctions. A: Diamond interchange with straight diamond ramps, B: Parclo B (2 quad) interchange with s-shaped and u-shaped ramps, C: Full cloverleaf interchange with cloverleaf and directional ramps, and D: All directional four leg interchange with directional ramps including flyover hook ramps.

AMF for interchange ramp design	Exit ramps	Entrance ramps
Straight diamond ramp	1.00	1.00
2-curved diamond ramp	1.32	0.93
S-shaped ramp	2.05	2.48
U-shaped ramp	4.11	4.15
Flyover hook ramp	5.15	5.26
Directional ramp (45-135 degrees)	1.07	1.42

Accident modification factors for interchange ramp design on exit and entrance ramps.

Based on Danish studies, AMFs for interchange ramp design have been estimated for exit and entrance ramps, see table above. These AMFs are in line with foreign studies, and also fit well with AMFs based on horizontal curves on ramps as shown in a previous section. Cloverleaf ramps are a typical design for direct connector ramps at motorway junctions, but are seldom used as a design for exit or entrance ramps. It has not been possible to estimate AMFs for cloverleaf ramps based on Danish data.

Speed limit

Danish studies clearly show significant differences in accident and injury rates for comparable motorways with speed limits of 110 and 130 kph respectively. The Danish results is consistent with foreign studies and models that also show clear correlations between speed and safety. Danish studies also show that the speed limit on motorways does not affect safety on ramps. It has not been possible to estimate reliable AMFs for speed limits below 110 kph in Denmark. The following AMFs are used for speed limits:

AMF for speed limit	Injury accidents	PDO accidents	Killed and severe injuries	Slight injuries
110 kph	0.79	0.94	0.66	0.82
130 kph	1.00	1.00	1.00	1.00

Accident modification factors for speed limit on motorway links, exit diverges and entrance merges.

Variable message signs and ramp metering

Variable message signs (VMS) are used for various reasons on motorways around the world, e.g. VMS are used in relation with hard shoulder running. There are also safety effects of VMS used for warning of queue and fog as well as effects of VMS for use for e.g. speed harmonization. However, the safety effects of VMS differ, which may be due to variations in the number of signs per km, sign display, hours of activation, and algorithms used to control the display of signs. It is therefore recommended to forecast the safety effects of individual projects with VMS, thus estimating AMFs for this. SPFs for motorway links, exit diverges, entrance merges and exit and entrance ramps are based on segments without VMS.

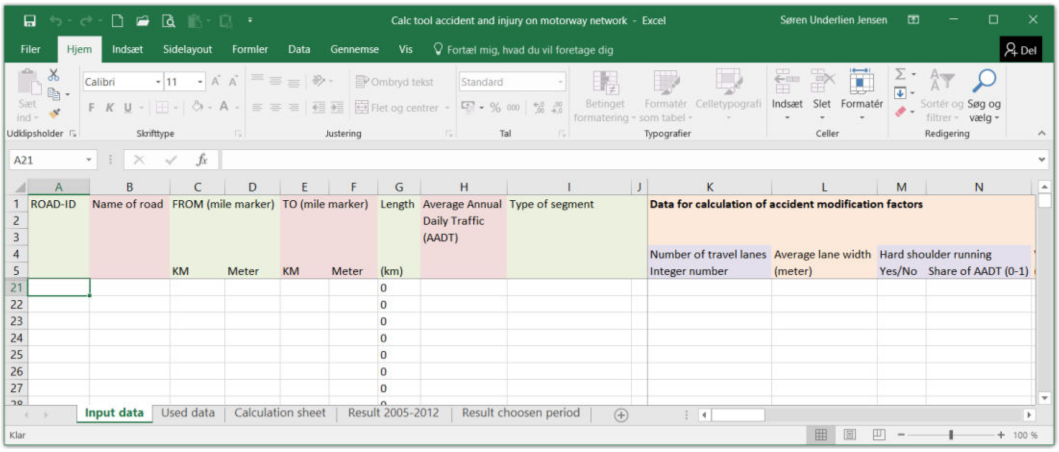
Studies show that ramp metering on entrance ramps reduces the number of accidents on the following entrance merge downstream, but only when the ramp metering system is active. None of the examined studies have identified the optimal location for the ramp metering traffic signal and stop line. The following AMF is used when ramp metering is active:

AMF for ramp metering	Entrance merges
Accidents and injuries	0.65

Accident modification factor for ramp metering on entrance ramp, the accident modification factor is only valid for the following entrance merge when the ramp metering system is active.

Calculation tool user manual

The calculation tool consists of an Excel spreadsheet, where safety performance functions, accident prediction models, accident modification factors, conversion and year factors are incorporated.



The calculation tool may estimate the expected number of accidents and injuries on a motorway network by entering data about length of segment, annual average daily traffic (AADT) and type of segment. This data is entered in the "Input data" sheet. Information about ROAD-ID and name of road can also be entered. The segment length is calculated if information about FROM and TO mile markers is entered, but length can also be entered in column G "Length" in km, where the 0-value is simply overwritten. AADT is entered for years for which an estimation of accidents and injuries is wanted. **Remember that it is AADT for the segment, i.e. only one side of the motorway – one direction of travel.** Type of segment is selected from the drop-down list with 15 different segment types.

Information used to calculate accident modification factors (AMF) may also be entered in the "Input data" sheet. The table on the next page specifies the entered values that are accepted by the calculation tool. Comments must be given to some input data used to calculate AMFs:

- ***Hard shoulder running:*** The share of AADT when hard shoulder running is active must be entered (hard shoulder running should only be active when the total traffic volume is higher than 1,350 vehicles per hour per travel lane – not including the hard shoulder as travel lane).

- ***Horizontal curves on motorways and ramps*:** If the entered curve lengths are longer than the segment length then the calculation tool automatically reduces the curve length so it is equal to the segment length. If no information about average speed at the beginning of the curve on a ramp is entered, the calculation tool automatically loads speeds that are common on ramps. However, these common speeds can differ significantly from average speeds actually driven or will be driven on the ramp. If information about curves on ramps is entered then AMFs for interchange ramp design is not used.

- ***Curve marking:*** The curve marking AMFs will only attain another value than 1.00 if one or two horizontal curves with radii of 600 meters or less have been entered for a motorway link, exit diverge or entrance merge. Curve marking only influences accident numbers in the curve, which is accounted for in the calculation of the AMFs.

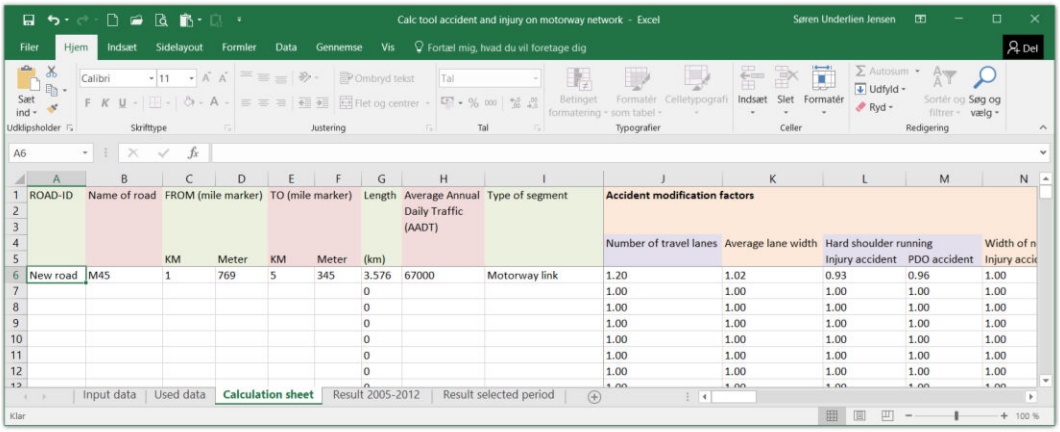
- ***Speed limit:*** If the speed limit on a segment are or are going to be changed to less than 110 kph it is recommended to choose a speed limit of 110 kph in the drop-down list.

- ***Ramp metering:*** The share of AADT on the entrance merge segment at time periods when ramp metering is active must be entered.

Column	Accepted values
Number of travel lanes – Integer number	1 ≤ number ≤ 21
Average lane width – (meter)	1,5 < width < 11
Hard shoulder running – Yes/No	Drop-down list (Yes, No)
Hard shoulder running – Share of AADT (0-1)	0 ≤ share ≤ 1
Width of nearside hard shoulder – (meter)	0 ≤ width < 11
Width of offside hard shoulder – (meter)	0 ≤ width < 11
Width of central reserve – (meter)	0 ≤ width < 101
Horizontal alignment motorway – Radius of curve – (meter)	10 < radius < 4.000
Horizontal alignment motorway – Length of curve – (meter)	0 < curve length ≤ segment length
Road lighting – Yes/No	Drop-down list (Yes, No)
Interchange ramp design – Type	Drop-down list (several options)
Horizontal alignment ramp – Radius of curve – (meter)	10 < radius < 1.000
Horizontal alignment ramp – Length of curve – (meter)	0 < curve length ≤ segment length
Horizontal alignment ramp – Average speed at start of curve – (kph)	4 < speed < 200
Curve marking – Yes/No	Drop-down list (Yes, No)
Speed limit – (kph)	Drop-down list (110, 130)
Ramp metering – Yes/No	Drop-down list (Yes, No)
Ramp metering – Share of AADT (0-1)	0 ≤ share ≤ 1

The "Used data" sheet shows the data that the calculation tool uses for estimating accidents and injuries. If no data for calculation of AMFs is entered in the “Input data” sheet then the calculation tool automatically specifies road design and traffic management on which the relevant SPFs are based upon. If a segment type is chosen where accident prediction models are used for estimating the expected number of accidents and injuries, then AMF data is always irrelevant. Entered data about other motorway segments, service areas or other ramps is not used for calculating

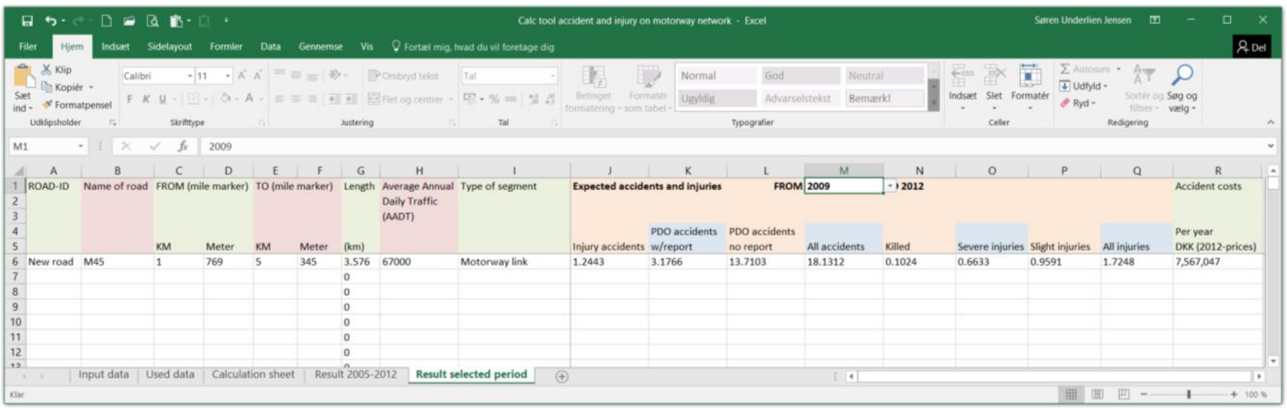
AMFs. The calculated AMFs can be found in the “Calculation sheet”. At the far right of this sheet are the results of estimations of the number expected accidents and injuries shown without the use of AMFs. This means you can see the number of accidents and injuries per year in the period 1999-2012 or 2005-2012 for the segment when AMFs are not used in the estimations.



The sheet "Result 2005-2012" shows the estimated expected number of accidents and injuries per year where AMFs are used. This sheet also shows the estimated accident costs.

It is not possible to enter data in the three sheets “Used data”, “Calculation sheet” and “Result 2005-2012”.

In the "Result selected period" sheet it is possible to select the first year of the period you wish to estimate accidents and injuries for. The choice of year is made in the drop-down list in column M. This sheet then gives the estimated expected number of accidents and injuries per year for the desired period where AMFs have been used. This sheet also shows the estimated accident costs.



Appendix 1. Accident prediction models

SPFs for motorway links, exit diverges, entrance merges and exit and entrance ramps are described in table 1.1. Also, accident prediction models for other types of motorway segments, service areas and other ramps are described in table 1.1. “Other motorway segments” are motorway diverges, motorway merges and motorway weaving segments.

Type of segment	Type of accident or injury	Estimated constants			Dispersion parameter, k
		a	p	b or b_1	
Motorway links	Injury accidents	0.00003113	0.8504		0.0874
	Single vehicle PDO accidents w/report	0.0001629	0.6383		0.0723
	Multiple vehicle PDO accident w/report	0.00000006798	1.4461		0.1129
	Single vehicle PDO accidents no report	0.0004523	0.6384		0.1208
	Multiple vehicle PDO accidents no report	0.0000000003404	2.0535		0.2030
	Killed and severe injuries	0.0001047	0.6906		0.3062
	Slight injuries	0.00003042	0.8384		0.9248
Exit diverges	Injury and PDO accident w/report	0.0002444	0.7365		0.4448
	PDO accidents no report	0.000001646	1.2856		0.1109
Entrance merges	Injury accidents	0.00003354	0.8287		0.0387
	PDO accidents w/report	0.000003632	1.1170		0.0336
	PDO accidents no report	0.000004229	1.1800		0.0514
Other motorway segments	Injury accidents	0.00006858	0.8086		0.4156
	PDO accidents w/report	0.00002311	1.0078		0.3360
	PDO accidents no report	0.000000002228	1.9267		0.4674
Service areas	All accidents	0.001556	0.8189		0.6456
Exit ramps	All accidents	0.003590	0.3195	-0.9530	0.6968
Entrance ramps	All accidents	0.0001619	0.7477		0.5996
Other ramps	All accidents	0.002313	0.6877		0.6721
Dual-way ramps				0.4732	
Direct connector ramps				1.0000	
Parallel ramps				0.1791	
Ramp diverges				0.1658	
Ramp merges				0.7831	
Ramp weavings				0.4399	

Table 1.1. *Recommended safety performance functions and accident prediction models for estimating the expected number of accidents and injuries on the motorway network. Models for ramps estimate the number of accidents per km per year in the period 1999-2012, while other models estimate the number of accidents per km per year in the period 2005-2012.*

Appendix 2. Conversion factors

Only in a few cases the recommended SPFs and accident prediction models for one type of segment in appendix 1 estimate the number of accidents and personal injuries divided into each accident and injury severity. An example is that a SPF may estimate the number of injury accidents for entrance merges. The result from this SPF is then used to calculate the number of killed, severe injuries and slight injuries respectively by using conversion factors that indicate e.g. the number of killed per estimated injury accident. The conversion factors are described in table 2.1. When using conversion factors it is assumed that the p-value is the same for each of the estimated accident and injury severities. Some preliminary accident prediction models indicate that this assumption is reasonable.

"Other motorway segments" are motorway diverges, motorway merges and motorway weaving segments. "Other ramps" are dual-way ramps, direct connector ramps, parallel ramps, ramp merges, ramp diverges and ramp weaving segments.

Type of segment	Model for …	Conversion factor – number per estimated accident or injury from SPF or accident prediction model					
		Injury accidents	PDO accidents w/report	PDO accidents no report	Killed	Severe injuries	Slight injuries
Motorway links	Fatalities and serious injuries				0.1338	0.8662	
Exit diverges	Injury and PDO accidents w/report	0.3407	0.6593		0.0296	0.1852	0.3111
Entrance merges	Injury accidents				0.1019	0.6111	0.8333
Other motorway segments	Injury accidents				0.0476	0.7381	0.6429
Service areas	All accidents	0.1429	0.5143	0.3429	0.0000	0.0857	0.0571
Exit ramps	All accidents	0.1611	0.2416	0.5973	0.0067	0.0940	0.0738
Entrance ramps	All accidents	0.0755	0.3019	0.6226	0.0000	0.0566	0.0377
Other ramps	All accidents	0.2500	0.2568	0.4932	0.0405	0.1554	0.1351

Table 2.1. *Conversion factors for calculating the number of accidents and injuries divided by accident and injury severity in relation to SPFs and accident prediction models in appendix 1.*

Appendix 3. Year factors

Accident prediction models (not SPFs) with year factors for motorway links, exit diverges, entrance merges, motorway diverges, motorway merges, motorway weaving segments and service areas have been developed. The models with year factors are based on 9,909 accidents and 2,081 injuries. It was not possible to estimate a reliable model for killed. Year factors have been estimated based on these models, see table 3.1. The year factors may along with SPFs and accident prediction models from appendix 1 be used to calculate the number of accidents and injuries for a single year. The year factor is simply multiplied on the result from the SPF or accident prediction model.

Type of accident or injury	Year factors for calculating accidents and injuries for single year							
	2005	2006	2007	2008	2009	2010	2011	2012
Injury accidents	1.3293	1.2551	1.3097	1.0208	0.9492	0.8225	0.7718	0.5415
PDO accidents w/report	1.2059	1.1572	1.1512	0.9308	0.8796	0.8740	0.8981	0.9034
PDO accidents no report	0.9871	1.0380	1.0736	0.9951	0.9956	1.1146	0.8797	0.9163
Killed and severe injuries	1.4624	0.9932	1.3034	0.9065	1.0855	0.8753	0.8183	0.5554
Slight injuries	1.3369	1.4216	1.3715	1.0895	0.8028	0.8383	0.6275	0.5120

Table 3.1. *Year factors for calculating the number of accidents and injuries for single years in relation to SPFs for motorway links, exit diverges and entrance merges as well as accident prediction models for motorway diverges, motorway merges, motorway weaving segments and service areas.*

Accident prediction models with year factors for all ramps have been developed. The models are based on 527 accidents. Models for injuries are problematic and not shown. Year factors have been estimated based on these models, see table 3.2. Year factors may along with SPFs and accident prediction models from appendix 1 be used to calculate the number of accidents and injuries for a single year. It is recommended to use year factors for injury accidents from 1999-2012 to calculate single years and then convert these to numbers of killed, severe and slight injuries.

Type of accident	Year factors for calculating accidents for single year							
	2005	2006	2007	2008	2009	2010	2011	2012
Injury accidents	0.6632	0.4801	1.0790	1.1941	0.9245	0.3100	0.6047	0.8819
PDO accidents w/report	1.0388	0.7692	1.1689	1.0516	0.9502	0.5345	0.6297	0.9235
PDO accidents no report	0.8435	0.5912	1.1189	1.1476	1.4428	1.7469	0.8718	1.1785

Table 3.2. *Year factors for calculation of accidents for single years in relation to SPFs for exit and entrance ramps and accident prediction models for other ramps.*

By using year factors, a-values are fundamentally changed while other estimated constants (p- and b-values) are unchanged. Historically, this approach is reasonable since p-values more or less have been relatively unchanged over decades.