Design Specific Safety Performance Functions and Related Crash Modification Factors for the Freeway and Rural Road Network

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ABSTRACT

The Danish Road Directorate commissioned Trafitec to develop tools that enable them to predict crashes, fatalities and injuries on a new or redesigned freeway or rural road, where the traffic regulation and road design have been specified.

Design specific safety performance functions (SPF) have been developed for the freeway and rural road network. The SPFs are negative binomial crash prediction models. However, a model is based on observations (links or intersections) of a highly specified design e.g. 4-armed roundabouts with one 6.5 m wide circulation lane, a central island of 30 m in diameter, aso. Crash modification factors (CMF) related to specified design elements, e.g. diameter of central island, have been recommended/estimated based on results from safety studies from around the world including new Danish studies.

Links, intersections and roundabouts were defined based on analyses. SPFs for the freeway network include models for exit ramps, entrance ramps, exit diverge areas, entrance merge areas and freeway links. SPFs for the rural road network include models for 4-armed roundabouts, 3- and 4-armed signalized intersections, 3- and 4-armed yield (give-way) intersections, and road links. Models for different severities of crashes and injuries have been estimated. Around 90 CMFs are recommended/estimated.

All SPFs and CMFs have been inserted into spreadsheets, which enable traffic planners to easily calculate numbers of crashes, fatalities and injuries on a new/redesigned freeway, rural road, ramp, intersection or roundabout.

Keywords: Safety Performance Function, Crash Modification Factor, Freeway, Rural Road

INTRODUCTION

The Danish Road Directorate (DRD) commissioned Trafitec to develop tools that describes road safety for alternative road and intersection design and traffic management when planning new freeways and rural roads or redesigning existing freeways and rural roads.

The tools are to solve two challenges that road administrations often encounter. One challenge is to predict crashes and injuries for a new freeway or rural road with a specified design, perhaps including several links and intersections making up a new network. Previously, the DRD could not meet that challenge, because their crash prediction models were not design specific, but only specified to different types of road like freeway, expressway, rural road with hard shoulders, etc. or to different types of intersection like 4-armed signalized intersection, 3-armed channelized yield intersection, etc. The second challenge is to predict a possible safety effect on crashes and injuries, when an existing freeway or rural road or intersection of a given design is redesigned to another freeway, rural road or intersection with a new specific design. An example: Traffic planners may find CMFs for converting an existing 4-armed signalized intersection to a 4-armed roundabout, but in reality, the safety effect of such conversion will depend heavily on both the specific design of the existing 4-armed signalized intersection and the specific design of the new 4-armed roundabout. Tools therefore have to include how road safety depends on e.g. the design of a 4-armed signalized intersection and the design of a 4-armed roundabout, i.e. CMFs related to specified types of road or intersection are needed.

For many years road standards have been in place, and many of the freeways and rural roads meet the recommended design when built in Denmark. This means that many km of freeway has more or less the same cross section, the same ramp design, aso., and likewise for rural roads, intersections and roundabouts. These 'dominating' design variants can be used to set up crash prediction models for design specific variants – i.e. design specific SPFs. If many CMFs are set up and many SPFs are estimated then it is possible to predict the number of crashes and injuries for most of the existing designs of links, intersections and roundabouts on the freeway and rural road network.

The purpose of the work DRD commissioned Trafitec to undertake can be further clarified to the following tasks:

- Develop and estimate reliable design specific SPFs for as many 'dominating' design variants on the freeway and rural road network as possible.
- Set up CMFs for design elements that have been specified for the estimated SPFs, e.g. width of nearside hard shoulder on links and central island diameter at roundabouts.
- Develop spreadsheets that include SPFs and CMFs enabling traffic planners to easily predict the number of crashes and injuries for freeways, rural roads, intersections and roundabouts of various design and traffic regulation.

Crash prediction models, i.e. SPFs, have been developed and estimated for many years. In most cases, it has been found that negative binomial (NB) models are a good – often the best – way to describe the relations between the density of crashes and injuries on one side and the exposure (traffic volumes) and factors related to road design, traffic regulation, etc. on the other side. A NB model has a Poisson-gamma distribution, and the dispersion parameter, k, describes how much the overdispersion is compared to a Poisson model, where the variance equals the sample mean. The dispersion parameter is very important, when SPFs are used to identify black spots or for evaluation purposes, e.g. a before-after safety study using Empirical Bayes.

In our case, we have choosen to use NB models to estimate design specific SPFs. However, the design specific SPFs are not to be used for identifying black spots, because non-design specific but only road and intersection type specific NB models are much better to identify black spots. The dispersion parameter for the estimated design specific SPFs is typically very small, which means that the amount of unexplained systematic variation in the density of crashes and injuries is very small. When the dispersion parameter is very small then almost none black spots will be identified.

Standard errors for intercept and independent variables of NB models could be used to describe the statistical uncertainty of the models. However, because a reliable description of statistical uncertainty for the CMFs was not possible, we chose not to describe statistical uncertainty for the developed tools, where SPFs and CMFs are combined.

METHODS

Before estimating SPFs and setting up CMFs it is needed to define units (links, intersections and roundabouts) that the SPFs are to represent. It is also needed to identify design elements that are possible to set up CMFs for and to describe the defined units by. This process involves lots of data collection, several preliminary analyses and search for results from safety studies that may be used for setting up CMFs. The process started by collecting existing data to build new databases. These data included:

- 1,170 km of freeway, with about 25 freeway interchanges, about 250 interchanges with other roads and about 90 service areas.
- 4,040 km of rural road, and about 400 roundabouts, 220 signalized intersections and 2,900 yield (give-way) intersections.

Location data, police-recorded crash data, traffic volume data, cross section data, alignment data, intersection design data, equipment data (like signs, lighting, safety barriers, aso.), and traffic regulation data (like speed limit, one-way or two-way traffic, overtaking ban, aso.) were collected for the units. Data on the "opening year" were also collected, meaning when the freeway, rural road, intersection and roundabout were opened to traffic and when the intersection was signalized.

One could estimate crash prediction models based on these new databases, but two preliminary analyses became very important. One preliminary analysis focused on how to model crashes and injuries for entrance merge and exit diverge segments on freeways. Here one could split crash data into crashes involving vehicles exiting or entering the freeway and crashes only involving through-going vehicles on the freeway. Then one could estimate a SPF for the freeway (crashes with only through-going vehicles) and an "add-on" SPF for the entry (crashes with entering vehicles) – and the combination of these two SPFs will enable a prediction of crashes and injuries for an entrance merge segment. However, this split of crash data is not possible in Denmark, because vehicles are not systematically split into through-going, exiting and entering vehicles.

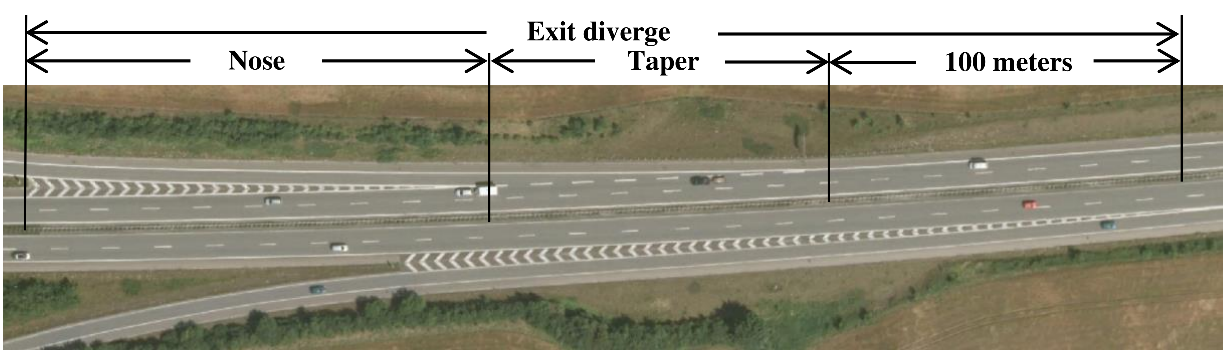

Figure 1 Definition of exit diverge on the freeway network

Therefore, we chose to set up SPFs for entrance merge and exit diverge segments, but this would need a clear definition of these segments. First, an exit diverge or entrance merge segment is on one side of the freeway, and it was decided that all SPFs for freeway segments had to be for just one side of the freeway, meaning that all location, crash, traffic volume … data had to be side specific. Analyses then showed that crash density was elevated 400 m after the taper ended at entrance merge segments, and that crash density was elevated 100 m before the taper started at exit diverge segments. It was defined that an entrance merge segment includes the 400 m of freeway with elevated crash density along with the sections with taper and nose, and exit diverge segment includes the 100 m of freeway with elevated crash density along with the sections with taper and nose, see example in **Figure 1**. These definitions also have the consequences that an exit ramp begins at the end of the nose of the exit diverge segment and ends at the intersection with the road crossing the freeway – and an entrance ramp starts at this intersection and ends at the start of the nose of the entrance merge segment. Some other preliminary analyses resulted in definitions of service areas, weaving segments, freeway diverge and merge segments, and different types af ramps at freeway interchanges. The purpose of these definitions was to have more homogenous units, so the crash density on especially freeway links did not depend on the length of the link.

The second very important preliminary analysis focused on how to split rural road links from intersections and roundabouts. An analysis showed that the crash density is at its highest at the center point of signalized intersections. The crash density then decrease rapidly as one moves away from the center point until one reaches a distance of approx. 20-25 m away from the center point of signalized intersections. Analyses of yield (give-way) intersections and roundabouts showed exactly the same, i.e. a decreasing crash density until one reaches a distance of approx. 20-25 m away from the center point. Due to these findings, the rural road network was then split into links, intersections and roundabouts as shown in the example in **Figure 2**.

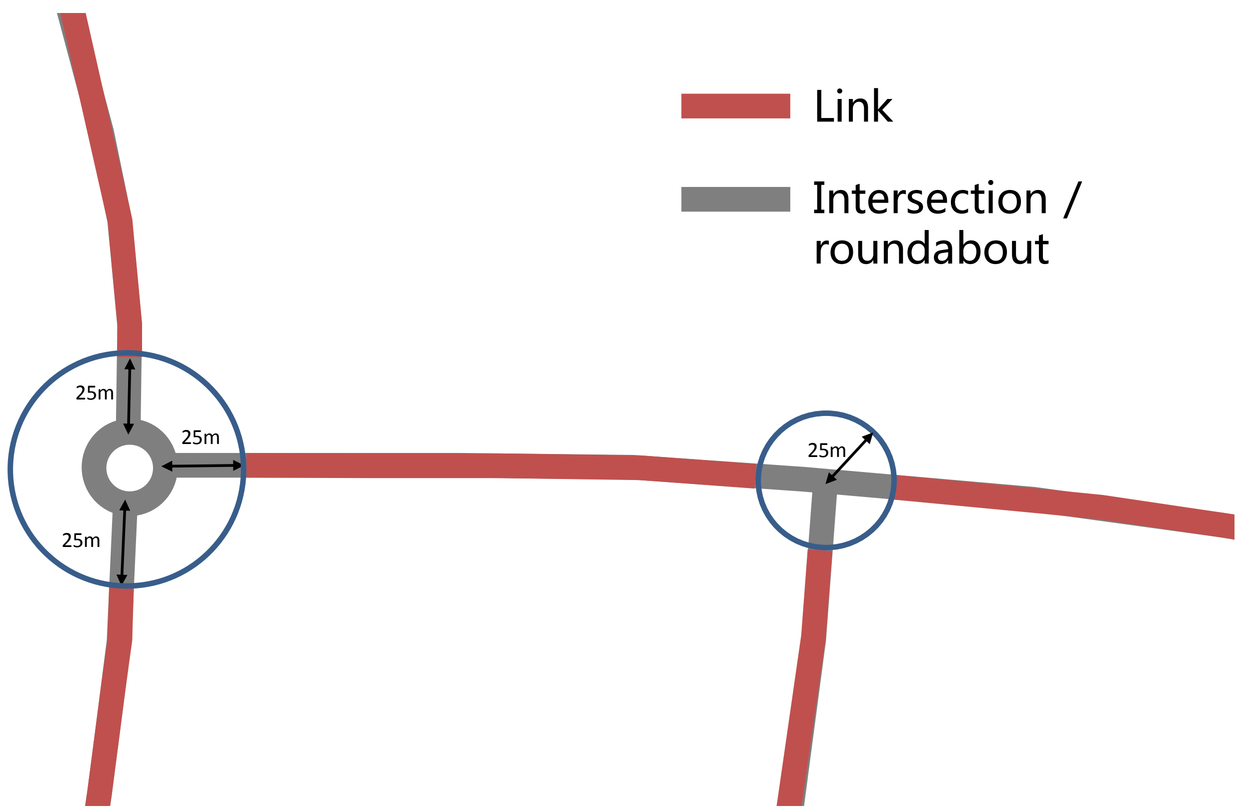

Figure 2 Definition of link, intersection and roundabout on the rural road network

The important preliminary analyses accompanied by other analyses enabled us to define the units that the SPFs are to represent. The databases with location data, police-recorded crash data, traffic volume data, cross section data, aso. were then changed so they matched the defined units. It was quickly realized that it was possible to set up CMFs for design elements, which was not described by the collected data. It was then decided, which “new” data should be collected through an inventory. Such new data included e.g. turn signals at signalized intersections, shunts (exclusive right-turn) at roundabouts, taper and nose length at merge and diverge segments along freeways, aso. Data on "major redesigns" was also collected, e.g. year for adding travel or turn lanes, widening hard shoulders, adding turn signals, establishing road lighting, aso. Other possible "new" data were judged too time consuming to collect compared to the benefits of having such data, e.g. data on milled rumble strips, corner radiies at intersections, exact placement of safety barriers relative to travel lanes/hard shoulders, aso. Here is given an example of the collected data, in this case for the freeway links (one driving direction):

- Exact location including police district, length of link and drive direction (north, northeast, east …).
- Police-recorded crash data including all accessible data e.g. year, crash type, severities, aso.
- Annual Average Daily Traffic (AADT) year by year.
- Cross section data; number and width of travel lanes, width of nearside and offside hard shoulders, and width of median.
- Alignment data; horizontal and vertical curves => bendiness and hilliness.
- Presence of curve marking.
- Presence of glare screen.
- Type of safety barrier in median.
- Total length of safety barriers in right hand side.
- Presence of road lighting.
- Presence of variable message signs.
- Presence of hard shoulder running scheme.
- Presence of overtaking ban for trucks.
- Presence of tunnel.
- Presence of 'keep distance' chevrons.
- Distance to service area up- and downstream.
- Speed limit and posted recommended speed.

Estimating SPFs

Before identifying dominating design variants and estimating SPFs, many thousands of crash prediction models were developed in order to: a) find the best function expressions for the SPFs, b) find variables besides traffic volumes that correlate significantly with crash and injury density, and c) if possible – estimate CMFs for some design elements.

The best working function expressions found for SPFs for freeway links, rural road links, exit diverges, entrance merges and entrance ramps are as follows:

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

where UHT is the crash 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 crashes or injuries per year) on the segment ($\mathrm{U} = \mathrm{a} \cdot \mathrm{L} \cdot \mathrm{N}^{\mathrm{p}}$).

For exit ramps the best working function expression of the SPFs is slightly different:

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

where UHT is the density of crashes per km per year, a, b_1 and p are estimated constants, L is the length of the exit 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 crashes per year) on the ramp ($\mathrm{U} = \mathrm{a} \cdot \mathrm{L} \cdot \mathrm{N}^{\mathrm{p}} \cdot e^{\mathrm{b}_1 \cdot \ln(\mathrm{L})}$).

For signalized and yield intersections the best working function expressions for the SPFs were:

$$\mathrm{UHT} = \mathrm{a} \cdot \mathrm{N}_{\mathrm{pri}}^{\mathrm{p}_1} \cdot \mathrm{N}_{\mathrm{sek}}^{\mathrm{p}_2} \qquad (3)$$

where UHT is the crash or injury density per intersection per year, a, p_1 and p_2 are estimated constants, and N_{pri} and N_{sek} are AADT on primary (major) and secondary (minor) road of the intersection. Traffic on any shunts of the intersection must be included in N_{pri} and N_{sek}.

The best working function expression for SPFs for roundabouts was:

$$\mathrm{UHT} = a \cdot (N_{pri} + N_{sek})^{p_1} \quad (4)$$

where UHT is the crash or injury density per roundabout per year, a and p_1 are estimated constants, and $N_{pri} + N_{sek}$ is the number of incoming vehicles (AADT) on all arms of the roundabout. Traffic on any shunts of the roundabout must be included in $N_{pri} + N_{sek}$.

It was found that NB models worked well for all estimated SPFs. For the SPFs for freeway links it was found that splitting crashes into single vehicle and multiple vehicle property-damage-only (PDO) crashes worked better than having all PDO crashes in one pool.

By setting up multivariate crash prediction models it was found that many of the design elements (variables) besides traffic volumes correlated significantly with crash and injury density. Some variables correlated so strongly that the variable had to be fully "eliminated" when choosing the dominating design variant or had to be part of the SPF. For e.g. freeway links, the strongly correlating variables were police district, width of nearside hard shoulder, number and width of travel lanes, speed limit, and presence of tunnels and 'keep distance' chevrons. For freeway links it was chosen to fully eliminate variance regarding width of nearside hard shoulder, number and width of travel lanes, and presence of tunnels and 'keep distance' chevrons. The variable for police district was kept part of the SPFs, and afterwards the SPFs were recalibrated to be valid for Denmark. Speed limit was partly eliminated to only include 110 and 130 km/h freeway links, and afterwards the SPFs were set to 130 km/h. Other significant variables were fully eliminated when choosing the dominating design variant for freeway links.

Multivariate crash prediction models were also used to estimate a few CMFs. The models also indicated a number of possible safety effects for other design elements, however, the statistical basis for those possible safety effects were not strong enough to an actual CMF estimation. The estimated CMFs were the following:

- *Width of nearside hard shoulders* on freeway links, exit diverges and entrance merges. There was a very clear linear relationship, where safety improved as the width of nearside hard shoulders became larger until it reached a width of 3 m.
- *Presence of service area* had no impact on safety on downstream freeway links.
- *Type of interchange ramp design* had very significant safety impact on exit and entrance ramps. An example is that straight diamond ramps were more than 4 times safer than U-shaped ramps.
- *Speed limit* had a very significant safety impact on freeway links, exit diverges and entrance merges. A 110 km/h speed limit was safer than 130 km/h speed limit.
- *One-way traffic on one or more arms* at both signalized and yield intersections resulted in a very significant improvement of safety at the intersections.
- *The total number of entry lanes* to roundabouts had a significant impact on PDO crash density.
- *Curvature or bendiness (degrees per km)* has significant safety impact on rural road links, where slightly curved links are safer than straight or very curved links.
- *The number of minor side roads and driveways per km* has significant safety impact on rural road links, where safety deteroiates as the number of side roads and driveways per km increases.

The chosen dominating design variants for which the design specific SPFs have been estimated are described in the result section.

Setting up CMFs

The SPFs only apply for a specific design and traffic management of respectively links, intersections and roundabouts. If the design of e.g. a link differs from the specific design or traffic management of the SPF, the predicted number of crashes can be estimated by using crash modification factors (CMFs).

A few CMFs have been set up by using results from the multivariate crash prediction models as shown in the previous section. However, most of the CMFs stem from literature studies. Here a few references have been very helpful, e.g. DRDs road safety handbook in Danish (DRD, 2014), Handbook of Road Safety Measures from the Norwegian Institute of Transport Economics (Høye et al., 2017), the cmfclearinghouse.org website, results from the NCHRP project 17-45 (Bonneson et al., 2012), and results from the EU-project Ripcord-Iserest (Dietze et al., 2008).

A systematic methodology to mathematically combining results from different safety studies like meta-analysis have not been used to set up the CMFs. There are three reasons to this. First, it is rather difficult to rate the quality of individual safety studies, and this is important because many – even larger – safety studies are of poor quality. Instead we have used common sence and only focused on results from studies of good quality. Second, some safety studies include results that are only partly relevant for the CMF being set up, e.g. road lighting along freeways have been studied several times, but there is a need to look for results from other types of road especially when it comes to the effect on fatalities. Again, we have to use common sence and assess if a partly relevant safety study result should enter our compilation of results from which we set up the CMF. Third, safety studies from other countries may not nesesarrily be transferred without reservations and used to set up a CMF in a Danish context, e.g. results from safety studies on width of offside hard shoulders on freeways in the USA may only be transferred to a Danish context with the reservation that safety effects related to that width may be to high, because several states in USA do not have a "keep to the right" rule on freeways. Again, common sense has to be used, in order to acknowledge to which degree a result from a safety study may be used to set up a CMF.

RESULTS

The results are split into three minor sections; SPFs and CMFs for the freeway network, SPFs and CMFs for the rural road network, and lastly the developed spreadsheets and applications.

SPFs and CMFs for the freeway network

SPFs have been estimated for five specific variants of freeway links, exit diverges, entrance merges, exit ramps and entrance ramps. SPFs can estimate the predicted numbers of crashes and injuries for those specific variants. SPFs apply to segments with the road design, equipment and traffic management as shown in **Table 1**.

All defined segments, SPFs and CMFs for the freeway network are described in the report *Road safety on motorways* (Trafitec, 2018a), which can be downloaded from www.trafitec.dk. Non-design specific crash prediction models for freeway merges, freeway diverges, freeway weaving segments, service areas, and different ramps at freeway interchanges are also described in the referenced report. The SPFs for freeway links are shown in **Table 2**. The function expression ($\mathrm{UHT} = \mathrm{a} \cdot \mathrm{N}^{\mathrm{p}}$) for these SPFs were described in the previous section Methods. The SPFs are based upon 525 freeway links with a total length of 902 km, where 4,001 crashes and 1,025 injuries were recorded in the years 2005-2012. Year factors for the period 2005-2012 have been estimated, so it is possible to predict the number of crashes and injuries for a single year e.g. 2012. However, these year factors are based upon a compiled set of SPFs for freeway links, exit diverges, entrance merges and crash prediction models from other freeway segments, and are not solely based on freeway links. On the basis of these SPFs it is possible to predict the number of crashes and injuries for the specific design variants of freeway links, exit diverges, entrance merges, exit ramps and entrance ramps that the SPFs represent.

TABLE 1 The specific design variants (observations) that safety performance functions for segments with one-way traffic (one direction) on the freeway network have been estimated upon. Note: ”-” = not relevant, ”*” = estimated

Road design, equipment and traffic management	Freeway 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
Average width of median	5.5 m	4.9 m	4.9 m	-	-
Horizontal curves - curve radius	≥ 4,000 m*	≥ 4,000 m*	≥ 4,000 m*	Straight diamond	Straight diamond
Safety barrier in median	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 km/h	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

TABLE 2 Recommended safety performance functions for estimating the predicted number of crashes and injuries on Danish freeway links. Models estimate the number of crashes or injuries per km per year in the period 2005-2012. Note: “w/report” is a crash, where the police have made an actual report about the crash including e.g. witness statements, alcohol breath tests, aso.

Type of crash or injury	Estimated constants		Dispersion parameter, k
	a	p	
Injury crashes w/report	0.00003113	0.8504	0.0874
Single vehicle PDO crashes w/report	0.0001629	0.6383	0.0723
Multiple vehicle PDO crashes w/report	0.00000006798	1.4461	0.1129
Single vehicle PDO crashes no report	0.0004523	0.6384	0.1208
Multiple vehicle PDO crashes no report	0.0000000003404	2.0535	0.2030
Fatalities	0.00001401	0.6906	0.3062
Severe injuries	0.00009069	0.6906	0.3062
Slight injuries	0.00003042	0.8384	0.9248

CMFs are linked to and can be used in relation to the developed design specific SPFs. By using SPFs in combination with CMFs a predicted number of crashes and injuries can be estimated for a large proportion of the existing freeway network with the current variation in road design and traffic management. The combination of CMFs and SPFs can also be used to estimate the predicted number of crashes and injuries for freeway networks with alternative road designs and traffic management in connection with planning and design of new freeways and freeway redesigns. Combining SPFs and CMFs is easy, one simply multiplies the CMF onto the result from the SPF, and one then gets the estimated, predicted number of crashes or injuries for the design that differs from the specific design that the SPF represents. The CMFs that have been set up are listed in **Table 3**.

TABLE 3 Recommended list of CMFs for the freeway network

CMF / Type of design	Freeway 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 median	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		

An example of a CMF for a design element on the freeway network is given here. Width of the median is between the edges of asfalted offside hard shoulders. Many studies from other countries than Denmark show that the number of crashes is reduced by about 1.0 % when the width of the median is widened by 1 m, while the number of injuries decreases by only about 0.3 %. Danish studies incate that the number of crashes is reduced by about 0.7 % and the number of injuries increases by about 0.2 % when the width of the median is widened by 1 m. We chose to have a CMF of 1.00 for injury crashes and injuries irrespectively of the width of median, i.e. the width of median is assumed not to impact the number of injury crashes and injuries. The CMF for PDO crashes were set to 1.00 for a 5 m wide median, and then increased by 0.01 as the median width decreased by 1 m, and then decreased by 0.01 as the median width increased by 1 m, i.e. the width of median is assumed to decrease the number of PDO crashes by 1.0 % as the width increase by 1 m. The CMF for PDO crashes is then 1.03, 1.02, 1.01, 0.97 and 0.94 for a median with of 2, 3, 4, 8 and 11 m respectively.

SPFs and CMFs for the rural road network

SPFs have been estimated for six specific variants of rural road links, intersections and roundabouts. SPFs can estimate the predicted numbers of crashes and injuries for those specific variants. SPFs apply to links, intersections and roundabouts with the design, equipment and traffic management as follows:

3-armed signalized intersections:

- AADT for all incoming vehicles is 3,000 – 40,000,
- Median islands (physical island in the middle) or median in all arms of the intersection,
- 2 left turn lanes,
- 1 right turn lane,
- No separation islands between turn lanes and lanes for straight ahead driving and no shunts,
- No bicycle facilities,
- Lighting of intersection and arms,

- No turning bans,
- Speed limit of 70 km/h,
- No turn arrow signals (neither right nor left), and
- Dual-way traffic in all arms of the intersection.

4-armed signalized intersections:
- AADT for all incoming vehicles is 3,000 – 40,000,
- Median islands or median in all arms of the intersection,
- 4 left turn lanes,
- 2 right turn lanes,
- No separation islands and no shunts,
- No bicycle facilities,
- Lighting of intersection and arms,
- No turning bans,
- Speed limit of 70 km/h,
- No turn arrow signals (neither right nor left), and
- Dual-way traffic in all arms of the intersection.

4-armed roundabouts:
- AADT for all incoming vehicles is 500 – 25,000,
- 1 circulating lane,
- A total of 4 entry lanes,
- 80 km/h speed limit,
- Central island diameter of 30 m,
- Central island height of 0.0-1.9 m,
- Width of truck apron next to central island is 2.0 m,
- Width of circulatory carriageway is 6.5 m,
- Triangular or trumpet shaped splitter islands on all arms,
- No shunts,
- No bicycle facilities,
- No pedestrian crossings,
- Lighting of roundabout and arms, and
- Dual-way traffic on all arms of the roundabout.

3-armed and 4-armed yield intersections respectively:
- AADT for all incoming vehicles is 500 – 25,000,
- 80 km/h speed limit on the primary (major) road,
- No median islands (ghost or physical island in the middle) on the primary (major) road,
- No median islands on the secondary (minor) road,
- No turn lanes, neither left nor right turn lanes,
- No bicycle facilities,
- No pedestrian crossings,
- No lighting of intersection or arms,
- No separation islands and no shunts,
- Obligation to give way (give way sign and marked yield line on the secondary (minor) road),
- No turning bans, and
- Dual-way traffic in all arms of the intersection.

Rural road links:

- AADT between 500 and 32,000,
- 2 travel lanes, one in each direction, each with a width of 3.5 m,
- 80 km/h speed limit,
- No median,
- Nearside hard shoulder width of 0.5 m,
- Width of shoulders (unpaved) of 2 m,
- No sidewalk,
- No road lighting,
- Maximum gradient of 2 %,
- 10 degrees curvature per km,
- Cycling allowed, and
- No side roads or driveways.

All defined units, SPFs and CMFs for the rural road network are described in the report *Road Safety on Rural Roads* (Trafitec, 2018b), which can be downloaded from www.trafitec.dk. The SPFs for 3-armed yield intersections are shown in **Table 4**. The function expression ($\mathrm{UHT} = \mathrm{a} \cdot \mathrm{N}_{\mathrm{pri}}^{\mathrm{p}_1} \cdot \mathrm{N}_{\mathrm{sek}}^{\mathrm{p}_2}$) for these SPFs was described in the previous section Methods. The SPFs are based upon 1,487 3-armed yield intersections, where 615 crashes and 189 injuries were recorded in the years 2011-2016. On the basis of SPFs it is possible to predict the number of crashes and injuries for the specific design variants of 3- and 4-armed signalized intersections, 4-armed roundabouts, 3- and 4-armed yield intersections and rural road links that the SPFs represent.

TABLE 4 Recommended safety performance functions for estimating the predicted number of crashes and injuries at 3-armed yield intersections in Danish rural areas. Models estimate the number of crashes or injuries per intersection per year in the period 2011-2016. Note: "w/report" is a crash, where the police have made an actual report about the crash

Type of crash or injury	**Estimated constants**			**Dispersion parameter, k**
	a	**p_1**	**p_2**	
Injury crashes w/report	0.000007283	0.6952	0.4186	0.2469
PDO crashes w/report	0.000011542	0.7246	0.4661	0.4233
PDO crashes no report	0.000002074	0.9263	0.3320	0.2170
Fatalities	0.000000558	0.6578	0.4892	3.1185
Severe injuries	0.000004634	0.6578	0.4892	3.1185
Slight injuries	0.000010884	0.6155	0.3850	6.1446

CMFs are linked to and can be used in relation to the developed design specific SPFs. By using SPFs in combination with CMFs a predicted number of crashes and injuries can be estimated for a large proportion of the existing rural road network with the current variation in road design and traffic management. The combination of CMFs and SPFs can also be used to estimate the predicted number of crashes and injuries for rural road networks with alternative road designs and traffic management in connection with planning and design of new roads, intersections and roundabouts and redesigns. Combining SPFs and CMFs is easy, one simply multiplies the CMF onto the result from the SPF, and one then gets the estimated, predicted number of crashes or injuries for the design that differs from the specific design that the SPF represents. The CMFs that have been set up are listed in **Table 5**.

An example of a CMF on the rural road network is given here. At roundabouts the number of arms may vary, and some arms only have one-way traffic, and some arms have shunts, and some roundabouts are multilane in the circulation. It was found that the best way to account for these variations of roundabout design was to have a CMF for the total number of entry lanes, where a 'one-travel-lane' shunt also counts as one entry lane. This means that there is no CMF for the number of arms, for one-way traffic on arms, for shunts, and for multilane circulation at roundabouts in **Table 5**. The total number of entry lanes at roundabouts have a clear relationship to safety at roundabouts. The number of entry lanes have no impact on injury crashes and injuries, and therefore we chose to have a CMF of 1.00 for injury crashes and injuries irrespectively of the number of entry lanes. However, an extra entry lane increases the number of PDO crashes by about 23 %. The CMF for PDO crashes were then set to 1.00 for 4 entry lanes, which is the number of entry lanes for the design specific SPFs for roundabouts. CMF for PDO crashes were set to 0.54, 0.77, 1.23, 1.46, 1.69, 1.92 and 2.15 for a roundabout with 2, 3, 5, 6, 7, 8 and 9 entry lanes respectively.

TABLE 5 Recommended list of CMFs for the rural road network

CMF / Type of design	3-armed signalized intersection	4-armed signalized intersection	4-armed round-about	3-armed yield intersection	4-armed yield intersection	Link
One-way traffic	X	X		X	X	
Number of turn lanes	X	X		X	X	
Left turn arrow signals	X	X				
Bicycle facility	X	X	X	X	X	
Speed limit	X	X	X	X	X	X
Number of entry lanes			X			
Splitter islands on arms			X	X	X	
Central island diameter			X			
Central island height			X			
Width of truck apron			X			
Width of circulation			X			
Road/intersection lighting			X	X	X	X
Type of priority				X	X	
Curvature						X
Gradient						X
Median						X
Width of travel lane						X
Width of nearside hard shoulder						X
Width of shoulder						X
Cycling ban						X
Side roads and driveways						X

Developed spreadsheets and applications

Three user-friendly spreadsheets have been developed due to the considerable number of calculations that needs to be undertaken to estimate the predicted number of crashes and injuries for part of a freeway or rural road network of a given design. The three spreadsheets include 1) freeway segments, 2) rural road links, and 3) intersections and roundabouts. In the "Input data" sheet, one has to type in AADT data for the link, segment or arms of the intersection or roundabout, and type in the length of the link or segment, and type in the number of arms of the intersection or roundabout. Having done the inputs, the spreadsheet calculates the predicted number of crashes and injuries for the design specific variant that the relevant SPFs represent. If one wants to predict safety for another design of the link or intersection, one simply types in the design that relates to the individual CMFs. Meaning that for 3-armed signalized intersections, one may change speed limit, add bicycle facilities, add turn arrow signals, change number of turn lanes, and change to one-way traffic on one or more arms. All other design elements of a signalized intersection can not be changed.

Spreadsheets make it easy to get reasonable predictions for the number of crashes and injuries even for larger networks of freeways and rural roads. One may use the spreadsheets to estimate safety for a new freeway or rural road or intersection, and one may operate with different alternative designs for the e.g. new freeway, and this way find the safest solution for the new freeway or the most cost-efficient design of the freeway. The spreadsheets also include calculations of crash and injury costs. One may also use the spreadsheets in order to estimate a safety effect of changing an existing design of a link or intersection to another design. An example: What will happen in terms of crashes and injuries if an existing 4-armed yield intersection is converted to a 4-armed signalized intersection or a 4-armed roundabout. Here one have to calculate the predicted number crashes and injuries both for the existing design and the new designs, because the safety effect is the differences in the predicted numbers of crashes and injuries, not the differences between recorded crashes and injuries for the existing design and the predicted number of crashes and injuries for the new designs.

The reports *Road safety on motorways* and *Road Safety on Rural Roads* (Trafitec, 2018a; Trafitec, 2018b) also includes user manuals for the spreadsheets and includes examples of how to calculate and use the spreadsheets for new roads and redesigns. The spreadsheets are in English versions and may also be downloaded from www.trafitec.dk.

UPDATES

Trafitec completed a study of driveways impact on safety of rural road links (Jensen et al., 2021). The study is based on 17,232 driveways and 3,147 crashes, and clearly shows that different types of driveways have different impact on safety. Trafitec is commissioned by the Danish Road Directorate to update all freeway SPFs and CMFs in 2022.

CONCLUSIONS

Design specific SPFs have been estimated for the freeway and rural road network in Denmark. For the freeway network, SPFs for freeway links, exit diverge and entrance merge segments, and exit and entrance ramps have been estimated. These SPFs enable traffic planners to estimate injury and PDO crashes, and fatalities, severe injuries and slight injuries, and crash and injury costs, for specific design variants of the freeway network. By setting up a great number of CMFs, the combination of SPFs and CMFs enable traffic planners to estimate safety for most of the existing freeway network, because the CMFs covers most of the variation in segment designs. By using the combination of SPFs and CMFs, one may predict the number of crashes and injuries for almost any new freeway including interchanges, and one may predict what will happen in terms of safety if an existing freeway were to be redesigned.

For the rural road networks, SPFs for 3- and 4-armed signalized intersections, 4-armed roundabouts, 3- and 4-armed yield intersections and rural road links have been estimated. These SPFs enable traffic planners to, among others, estimate crashes and injuries at intersections and roundabouts between rural roads and freeway ramps. However, these SPFs also enable traffic planners to estimate injury and PDO crashes, and fatalities, severe injuries and slight injuries, and crash and injury costs, for specific design variants of the most of the other parts of the rural road network. Again, by using the combination of SPFs and CMFs, one may predict the number of crashes and injuries for almost any new rural road or new intersection or roundabout in rural areas, and one may predict what will happen in terms of safety if an existing rural road, intersection or roundabout were to be redesigned.

REFERENCES

Bonneson, J. A., S. Geedipally, M. P. Pratt and D. Lord. *Safety Prediction Methodology and Analysis Tool for Freeways and Interchanges*. Final report of project 17-45, National Cooperative Highway Research Program, USA, 2012.

Dietze, M., D. Ebersbach, C. Lippold, K. Mallschützke, G. Gatti and A. Wieczinski. *Safety Performace Function*. Eu-project Ripcord-Iserest, Deliverable D10, TÜD, Germany, 2008.

DRD. *Håndbog Trafiksikkerhed: Effekter af vejtekniske virkemidler, 2. udgave* [Road safety handbook: Effects of road safety measures, second edition]. Report 507, Danish Road Directorate, Copenhagen, Denmark, 2014.

Høye, A., R. Elvik, T. Vaa and M. Sørensen. *Trafikksikkerhetshåndboken* [The handbook of road safety measures]. Institute of Transport Economics, Oslo, Norway, Norwegian website edition at tsh.toi.no accessed 7 August, 2017.

Jensen, S. U., Andersson, P. K. and J. W. Sall. *Vejadgange og trafiksikkerhed* [Driveways and road safety]. Trafitec, Søborg, Denmark, 2021.

Trafitec. *Road safety on motorways: Accident prediction models, accident modification factors and user manual for calculation tool*. Trafitec, Søborg, Denmark, 2018a.

Trafitec. *Road Safety on Rural Roads: Handbook of accident prediction models, accident modification factors and user manual for calculation tools*. Trafitec, Søborg, Denmark, 2018b.