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The relationship between collisions and skid resistance on the Strategic Road Network

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Executive Summary

Road surface friction on the Strategic Road Network (SRN) is managed through the requirement to provide skid resistance and texture depth. The requirements have been in place since the 1980s and were last reviewed prior to the 2004 update to the skid resistance Standard (HD28). Given the changes that have occurred in recent years to the SRN, including the introduction of Smart motorways and widespread adoption of negatively textured pavement surfacing materials, and to the vehicle fleet, for example anti-lock braking systems and electronic stability control systems are now widespread, a further review of the current approach is appropriate.

This task undertook similar analyses to those reported in TRL 622 (Parry & Viner, 2005) to examine the relationship between skid resistance, collision risk and other characteristics. The analysis presented in this report is restricted to rural roads on the SRN (i.e. those roads with a posted speed limit of 40mph or more), since there is insufficient length of the network in urban areas for a robust analysis. The analysis also makes use of traffic, collision and condition data.

The relationship between collision risk and skid resistance was investigated. The overall levels of collision risk are similar to those observed in the previous analysis. However, the previous work showed a downward trend for collision risk with increasing skid resistance - this was marked for non-event sections on carriageways with two-way traffic, less strong for carriageways with one-way traffic and ambiguous for motorways (site categories C, B and A as defined in HD28/15). In the current analysis, these trends are less pronounced. This work found that while the overall collision risk increases from site category A, to B to C, as before, the influence of skid resistance on the level of risk in categories B and C was seen to be much reduced. Nonetheless a small increase in the proportion of collisions in wet conditions on sections with lower skid resistance was still evident. With the exception of categories Q and K (approaches to junctions and pedestrian crossings) stronger, downward, trends were observed for most ‘event’ sections. On roundabouts the risk of collision in the wet was seen to double on sections with low skid resistance (note there was a low sample size); on bends and gradients the risks of wet collisions, and of wet skidding collisions, were seen to decrease as skid resistance increased.

A multivariate regression technique known as Generalised Linear Modelling was used to investigate the relationship between collisions and a number of variables including skid resistance. The results presented can be used to give an indication of the direction of the relationship between the significant variables and collision numbers, but not to predict the actual number of collisions expected on a given section.

Texture depth appears in all the models for all collisions with the exception of the gradients category. However, this property doesn’t seem to be only associated with preventing vehicles skidding on wet roads. It may be more generally associated with an increased road surface friction in all conditions. Traffic flow is always significant as an explanatory variable in the models.

The following recommendations are made as a result of this work:

1. For bends and gradients the skid resistance exhibits a significant influence on collision risk. While this study does not demonstrate a causal link, sections with higher skid resistance currently exhibit lower risk of collisions and fewer collisions in

wet conditions. Treatments to these sites identified by the current Standard should be prioritised and the practicality of achieving a cost effective and sustainable solution through enhanced skid resistance, or other options for reducing risk, should be considered.

2. The situation is similar for roundabouts, although the current study is limited by the lack of availability of traffic data, texture and geometry data, on roundabouts. This could potentially be addressed through a study of collision numbers (as opposed to rates), an approach that could potentially be extended to slip roads, for which traffic data were mainly unavailable in this study.
3. No change is recommended to the ILs for non-event categories A-C.
4. No change is recommended to the ILs for junctions (category Q) and pedestrian crossings (K).

1 Introduction

Road surface friction on the English Strategic Road Network (SRN) is managed through the requirement for skid resistance and texture depth. The requirements have been in place since the 1980s and were last reviewed prior to the 2004 update to the skid resistance Standard (HD28). Given the changes that have occurred in recent years to the SRN, including the introduction of Smart motorways and widespread adoption of negatively textured pavement surfacing materials, and to the vehicle fleet, for example anti-lock braking systems and electronic stability control systems are now widespread, a further review of the current approach is appropriate.

This task aimed to undertake similar analyses to those reported in TRL 622 (Parry & Viner, 2005) to examine the relationship between skid resistance, collision risk and other characteristics. This has been undertaken considering the different road types and geometries (site categories) defined in the Standard. The data sources used in this analysis are described in Section 2. Exploratory analysis of collision risk is reported (Section 3), followed by statistical modelling of the factors that influence the risk (Section 4).

The analysis presented in this report is restricted to rural roads on the SRN (i.e. those with a posted speed limit of 40mph or more), since there is insufficient length of the network in urban areas for a robust analysis.

1.1 Current approach to managing skid resistance

Within the current Standard, HD28, the approach to managing appropriate levels of skid resistance is based on routine measurements, the data from which trigger investigations of individual sites where the skid resistance is low. The thresholds to trigger site investigations (Investigatory Levels, ILs) are indicated in Table 1. The results of these investigations determine the justification and relative priority for maintenance treatment to improve the surface condition (Highways Agency, Transport Scotland, Welsh Government and Department for Regional Development Northern Ireland, 2015).

In Table 1, dark shading indicates the range of ILs that will normally be used on the SRN for each type of site. Lighter shading indicates lower ILs that can be used for low risk situations, such as locations with low traffic or where the risks normally present are mitigated. The overall concept is that higher ILs are assigned at locations where the risk of collisions involving skidding is greater, thereby attempting to achieve an equalisation of risk. Previous analyses of the relationship between collision risk and skid resistance have informed:

- The definition of the different site categories present in the table
- The range of IL applicable for each site category, and
- Factors to consider when selecting the most appropriate IL from within the range and when carrying out site investigations

Table 1 Site categories and Investigatory Levels from HD28/15[1]

Site category and definition		Investigatory Level for skid resistance					
		0.30	0.35	0.40	0.45	0.50	0.55
A	Motorway	▨	■				
B	Non-event carriageway with one-way traffic	▨	■	■			
C	Non-event carriageway with two-way traffic		▨	■	■		
Q	Approaches to and across minor and major junctions, approaches to roundabouts and traffic signals				■	■	■
K	Approaches to pedestrian crossings and other high risk situations					■	■
R	Roundabout				■	■	
G1	Gradient 5-10% longer than 50m				■	■	
G2	Gradient >10% longer than 50m				▨	■	■
S1	Bend radius <500m – carriageway with one-way traffic				■	■	
S2	Bend radius <500m – carriageway with two-way traffic				▨	■	■

1.2 Collisions on the Strategic Road Network

The definition of the Strategic Road Network changes as new roads are built and others pass from the control of Highways England to Local Authorities. In 1998 as part of a review of the road network, a report published by the Department of the Environment, Transport and the Regions (A New Deal for Trunk Roads in England) identified a core network of existing trunk roads which served a strategic national purpose and should remain the responsibility of the Secretary of State. The remainder, amounting to approximately 30% of the total trunk road network at the time, were deemed to serve regional or local purposes and were to be de-trunked.

The previous work (Parry & Viner, 2005) used collision data from 1994 to 2000 and was based on the 1999 Trunk Road Network. Since then, the de-trunking programme has taken place. The roads that passed to Local Authority control were, on average, constructed to a lower standard of geometric design than those that remained within the SRN and this may have affected the trends with skid resistance that are studied here.

Figure 1 shows the number of casualties on the SRN by road class and severity from 2000-2013.

[1] Refer to original source for additional notes

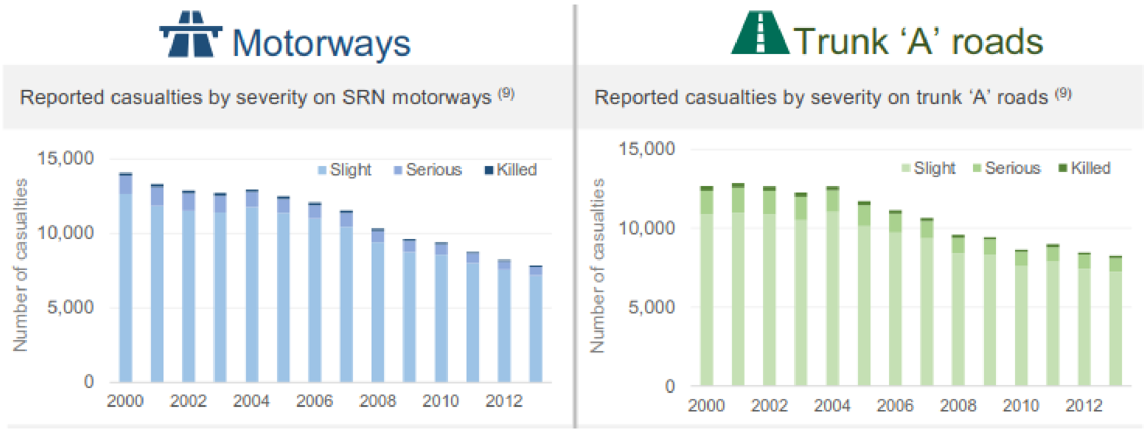


Figure 1: Reported casualties on the SRN by road class and severity (2000-2013) Reprinted from Department for Transport (2015)

The number of collisions and casualties on the SRN has fallen, continuing a long term downwards trend. In contrast, motor vehicle traffic on the SRN has increased since 2000 (see Figure 2). The fatal and serious collision rate has reduced due to a combination of road, vehicle and behavioural improvements. The slight collision rate has also reduced, although some of this reduction may be due to be changes in reporting levels.

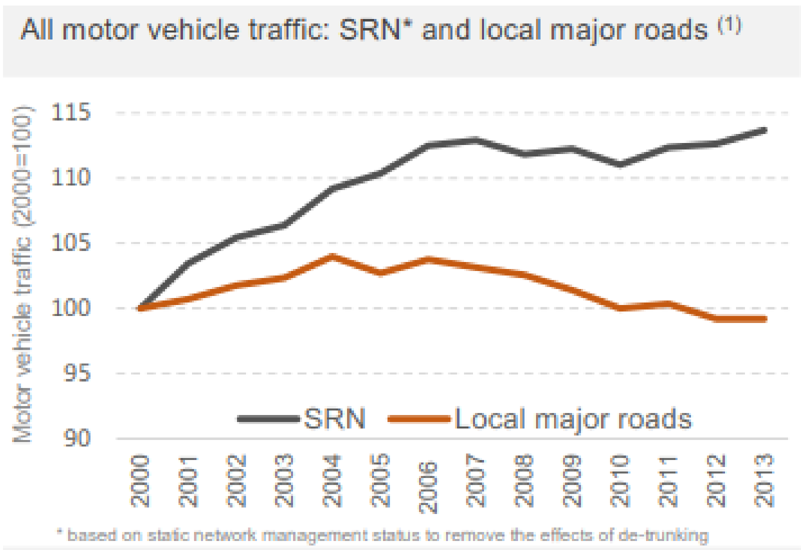


Figure 2: Motor vehicle traffic on the SRN (2000-2013) Reprinted from Department for Transport (2015)

The SRN continues to change with the development of Smart motorways in recent years. These include controlled motorways (with variable speed limits), hard shoulder running (HSR) where the hard shoulder is opened as a running lane at busy times and all lanes running (ALR) where there is no hard shoulder.

Some limited evaluation of the impact of these motorways has been carried out (Mott MacDonald (2011); Highways England (2016a, 2016b)), with the one year evaluations of the M25 ALR schemes concluding that "the results provide an initial indication that safety has not worsened as a result of the scheme". However, these evaluations are only short-term evaluations and thus the longer term impact of these schemes is currently unknown.

2 Data sources

The following data sources have been used for this analysis:

- Stats19 (Collision data)
- HATRIS (Traffic data)
- HAPMS (Road network and condition data)

These are described in more detail below.

2.1 Collision data

The Stats19 database contains information on all reported collisions in Great Britain that involved injury. This includes details about the circumstances of the collision (including road, location and road surface condition) and the vehicles involved (including whether the vehicle skidded during the collision). The data include fatal, serious and slight collisions. Whilst most, if not all fatal collisions are reported to the police, it is likely with the lower severity collisions that not all collisions are reported, and that the level of reporting may have changed over time.

Data were extracted from Stats19 for all collisions on the Strategic Road Network (as defined using the 2010 network definition) between 2010 and 2013 inclusive (4 years). The following definitions were used for specific analyses:

- ‘Wet collisions’ were defined as: road surface condition = 2 ‘wet/damp’ (snow, frost/ice, flood are not included)
- ‘Skidding collisions’ were defined as: vehicle skidding = 1 ‘skidded’, 2 ‘skidded and overturned’, 3 ‘jack-knifed’ or 4 ‘jack-knifed and overturned’ (overturn alone not included)

2.2 Traffic data

Highways England traffic data are stored in the HATRIS database. This includes average annual daily flows on each link of the SRN. A copy of the HATRIS database held at TRL was used to estimate the traffic on each section using data from 2010 to 2013; traffic was available for about 70% of the sections. Sections with no traffic data were excluded from the analysis since the collision rate cannot be calculated.

2.3 Road network data

Highways England’s HAPMS database contains contextual information for each section, to allow analysis by environmental factors such as rural or urban, geometric factors such as radius of curvature, gradient and crossfall, and speed limit.

2.4 Road condition data

Pavement condition data were extracted from routine machine surveys stored in HAPMS, particularly skidding resistance by site category. Depending on site category, the road network is stored in 10m, 50m or 100m sections, with each section being surveyed once per year between 2010 and 2013[2]. Surface texture and rut depth were downloaded for each 100m length for the same period.

2.5 Aggregation of data

The network used in this analysis was defined by combining data into sub-sections of predetermined lengths within the ten site categories defined in the 2015 skid resistance Standard (A, B, C, Q, K, R, G1, G2, S1 and S2). The preferred lengths were selected to be 500m for motorways and 200m for all other roads; this aligns with the methodology used in the previous study (Parry & Viner, 2005). However, categories Q (approaches to junctions and traffic signals) and K (approaches to pedestrian crossings) are generally used for the 50m approach to those features, therefore the typical length for analysis of these categories is shorter.

Data were combined from the different data sets to give the following data for each section[3] on the network for each year between 2010 and 2013:

- Length
- Annual Average Daily Traffic (AADT)
- Number of collisions
- Number of wet collisions
- Number of wet skid collisions
- Site category (consistent for each analysis length)
- Average skid resistance
- Average rut depth
- Average texture depth
- Average crossfall
- Maximum gradient
- Tightest radius

Exploratory modelling showed that year was not a significant predictor of collision risk so the data from individual years was combined (using the section ID) to create a dataset with one row per sub-section (as defined above). Network sections were included in the analysis when at least three of the four years of SCRIM data were available[4].

[2] 2013 data were the most recent available at the time of the study.

[3] For two-way roads, each direction was treated separately in the analysis.

[4] A small number of rows (55) were excluded because the difference between the maximum and minimum SCRIM values for the four years was considered to be too great (>|0.5|) and a small number (92) were excluded because the length of the section was small (<40m).

2.6 Summary of data available for analysis

The aggregated dataset available for analysis is shown by site category in Table 2. This shows the length of network, traffic, number of collisions and the collision rate. Also shown is the percentage of length for which traffic data were available.

Table 2: Summary of data available for analysis

Site category		Length with AADT (km)	100MVehkm	Total collisions (2010-13)	Collisions per 100Mvehkm per year	% of length with AADT
A	Motorway	3,968	2,239.8	10,265	4.6	79%
B	Non-event carriageway with one-way traffic	3,644	1,045.7	6,708	6.4	61%
C	Non-event carriageway with two-way traffic	1,594	182.5	1,935	10.6	94%
Q	Approaches to and across minor and major junctions, approaches to roundabouts and traffic signals	296	45.6	1,728	39.5	67%
K	Approaches to pedestrian crossings and other high risk situations	7	1.2	68	57.6	62%
R	Roundabout	15	2.4	233	100.2	17%
S1	Bend radius <500m – carriageway with one-way traffic	72	20.1	304	15.2	21%
S2	Bend radius <500m – carriageway with two-way traffic	140	15.6	336	21.6	64%
G1	Gradient 5-10% longer than 50m	147	23.2	278	11.9	80%
G2	Gradient ≥10% longer than 50m	2	0.3	6	19.8	80%
TOTAL		**9,886**	**3,575**	**21,915**	**6.0**	**71%**

The number of collisions per vehicle kilometre is lowest on motorways (4.6 collisions per hundred million vehicle-kilometres) and highest on roundabouts (100 collisions per hundred million vehicle-kilometres).

However, caution should be taken when interpreting the figures for roundabouts since only a small proportion (17%) of the network for this category has traffic data available. As a result, it will not be possible to draw robust conclusions about this site category. Some analysis on the subset of the network with traffic data available is presented in Section 3 but it has not been possible to develop statistical models for roundabouts since information on the geometry and surface condition of these road sections are not available.

In addition, for the purposes of this analysis some other categories have been combined:

- There is a short length of network with site category G2 (2km), on which there were 6 collisions in 4 years. The small numbers mean that analysis on these sections alone is not robust so these were combined with category G1. As category G2 is essentially non-existent on the SRN in England, this is not a major limitation for Highways England, but the other UK Overseeing Organisations may wish to extend this analysis.
- Similarly, category K is a small category (7km) and thus was combined with category Q. These categories have similar characteristics, both potentially requiring a vehicle to be able to give way at a defined position, and they are mainly separated in the Standard only due to the more serious likely outcomes for the pedestrian category.
- The S1 and S2 categories are also combined in the analysis and modelling since the length and the number of collisions on these is small. This is a more serious limitation of the data since a low proportion of the S1 category has traffic data available. This is because almost three-quarters of the sections in this category are on slip roads, which are not covered by traffic data; therefore the S1 category will be under represented in the analysis.

Table 3 shows the proportion of collisions which are fatal or serious for each of the site categories.

Table 3: Percentage of collisions which are fatal or serious by site category

Site category		Total collisions	% of collisions which are fatal	% of collisions which are fatal or serious
A	Motorway	10,265	2%	13%
B	Non-event carriageway with one-way traffic	6,708	3%	17%
C	Non-event carriageway with two-way traffic	1,935	5%	24%
Q & K	Approaches to and across minor and major junctions, approaches to roundabouts and traffic signals Approaches to pedestrian crossings and other high risk situations	1,850	3%	17%
R	Roundabout	233	0%	11%
S1 & S2	Bend radius <500m – carriageway with one-way traffic Bend radius <500m – carriageway with two-way traffic	640	3%	18%
G1 & G2	Gradient 5-10% longer than 50m Gradient ≥10% longer than 50m	284	5%	20%

A higher proportion of collisions are fatal or serious on two-way traffic sections than on one-way traffic sections or motorway sections. This is likely due to the standard to which these roads are built; despite the typically faster speeds, median barriers on motorways and carriageways with one-way traffic aim to prevent head-on collisions which often result in more severe injuries.

Similarly, relatively few collisions at roundabouts are fatal or serious due to the slower speeds and relative alignment of vehicles at these locations.

Table 4 shows the proportion of collisions which are in wet conditions, and the proportion of these collisions which involve skidding, for each of the site categories.

Table 4: Percentage of collisions which are wet or wet skid by site category

Site category		Proportion of all collisions which are in wet conditions	Proportion of collisions in wet conditions which involve skidding
A	Motorway	29%	47%
B	Non-event carriageway with one-way traffic	30%	49%
C	Non-event carriageway with two-way traffic	28%	35%
Q & K	Approaches to and across minor and major junctions, approaches to roundabouts and traffic signals Approaches to pedestrian crossings and other high risk situations	27%	33%
R	Roundabout	21%	32%
S1 & S2	Bend radius <500m - carriageway with one-way traffic Bend radius <500m - carriageway with two-way traffic	35%	48%
G1 & G2	Gradient 5-10% longer than 50m Gradient ≥10% longer than 50m	36%	52%

Around 30% of collisions on motorways (category A) and non-event carriageways with one-way traffic (B) occurred in wet conditions, and close to 50% of those involved at least one vehicle skidding or jack-knifing.

The proportion of collisions that occurred in wet conditions is similar for categories C and Q & K, but proportionately lower on roundabouts, approximately 20%. For these site categories, the proportion of wet collisions that involved skidding is lower than for A-B, between 30-35%.

In contrast, on bends and gradients a higher proportion of collisions happen in wet conditions than for the other site categories, and approximately 50% of these involve skidding.

3 Exploratory analysis of collision risk

This section presents the results of exploratory analysis into how collision risk varies with skid resistance. Collision risk is calculated as the total number of collisions divided by the total amount of traffic (measured in vehicle kilometres). Sections with no collisions are included if there is road length and traffic data available.

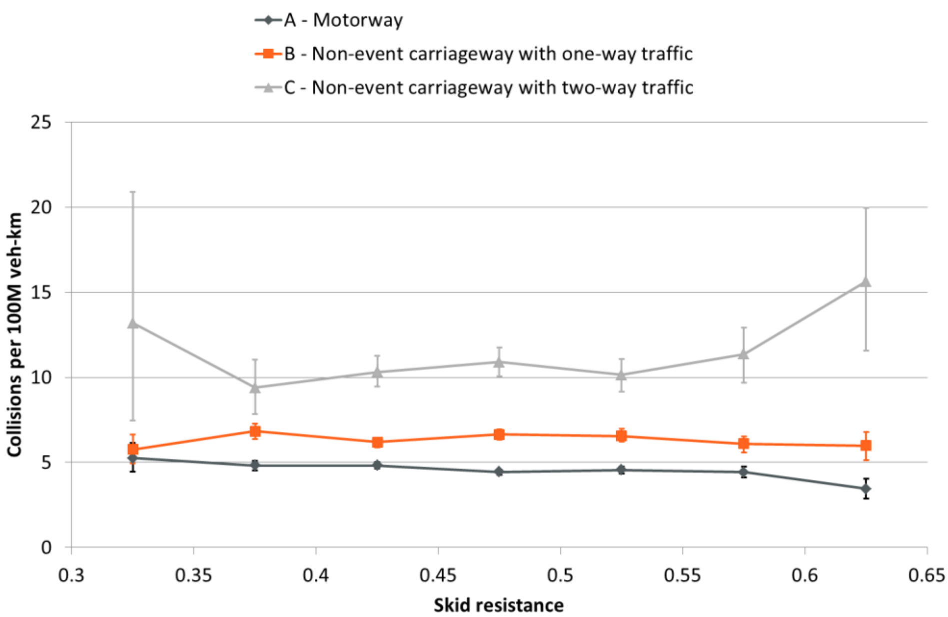
Within each chart, average skid resistance for each section is grouped into bands of width 0.05. For example, a skid resistance of 0.325 represents the range of data with values greater than or equal to 0.30 and less than 0.35. Sections with values of skid resistance lower than 0.30 and higher than 0.65 have been excluded from the analysis since these represent a very small proportion of the network used in this analysis (0.1% and 0.3% of the network length respectively).

The number of collisions is subject to random variation. Therefore the charts in the following sections show an error bar for each collision risk, based on the Poisson distribution of total number of collisions[5]. This gives a 95% confidence level on the number of collisions, that is, there is a 95% likelihood that the number of collisions lies within this range. The collision figures are then divided by the amount of traffic to give the error bars presented in the charts below. Note that, as no account of the confidence interval in the traffic figures is possible, it is possible that the true range for each risk is bigger.

3.1 Non-event categories (A, B and C)

Figure 3 shows the collision rates (per veh-km) for non-event sites by skid resistance.

Figure 3: Collision risk by skid resistance for non-event sections



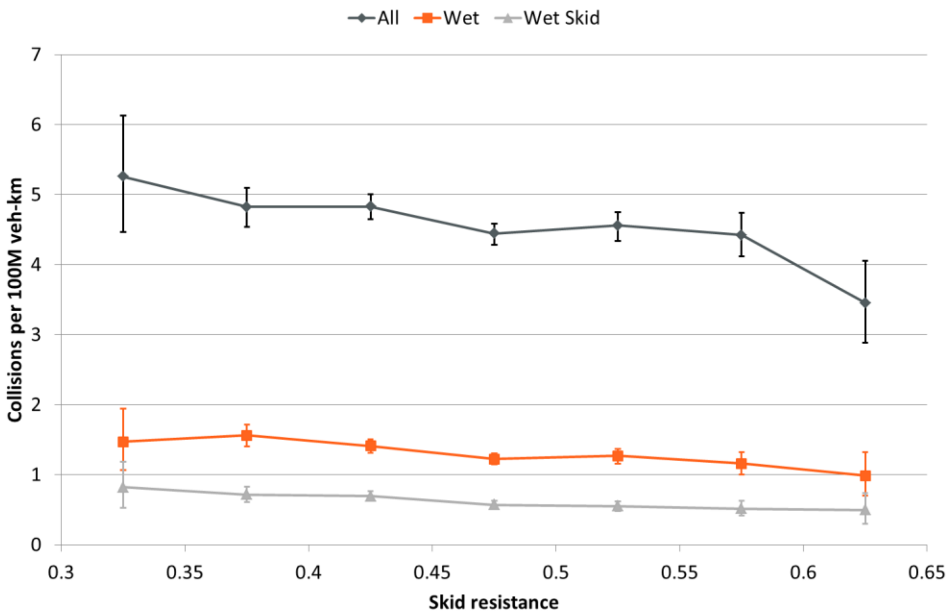
5Errors calculated in Excel as: Lower limit = IF(N>0,(CHIINV((95%+1)/2,2*N)/2),0), Upper limit = IF(N>0,CHIINV((1-95%)/2,2*(N+1))/2,CHIINV((1-95%)/2,2)/2)

This shows that the collision risk is lowest on motorways and highest on non-event carriageway with two-way traffic (as expected). Note that there are relatively few sections (and thus relatively few collisions) at the lowest and highest levels of skid resistance and so caution should be taken when interpreting these results. The error bars for collision risk help to indicate this, as the error bars are bigger when the risk is based on fewer collisions.

A comparison of the results in this study to those observed in the previous study (Parry & Viner, 2005) can be found in Appendix A (note that this comparison is restricted to motorways, one-way and two-way non-event sections since results from the other site categories are not comparable due to the fact that some categories have been combined for this analysis). The overall levels of collision risk are similar to those observed in the previous analysis. However, the previous work showed a downward trend for collision risk with increasing skid resistance - this was marked for non-event sections on carriageways with two-way traffic, less strong for carriageways with one-way traffic and ambiguous for motorways. In the current analysis, these trends are less pronounced.

The following charts in this section show each of the trends presented in Figure 3 in more detail. Figure 4 shows the collision risk, wet collision risk and wet skid risk for site category A (motorways). Note that the traffic data are available as AADT only and the same divisor is used for each of the three risks.

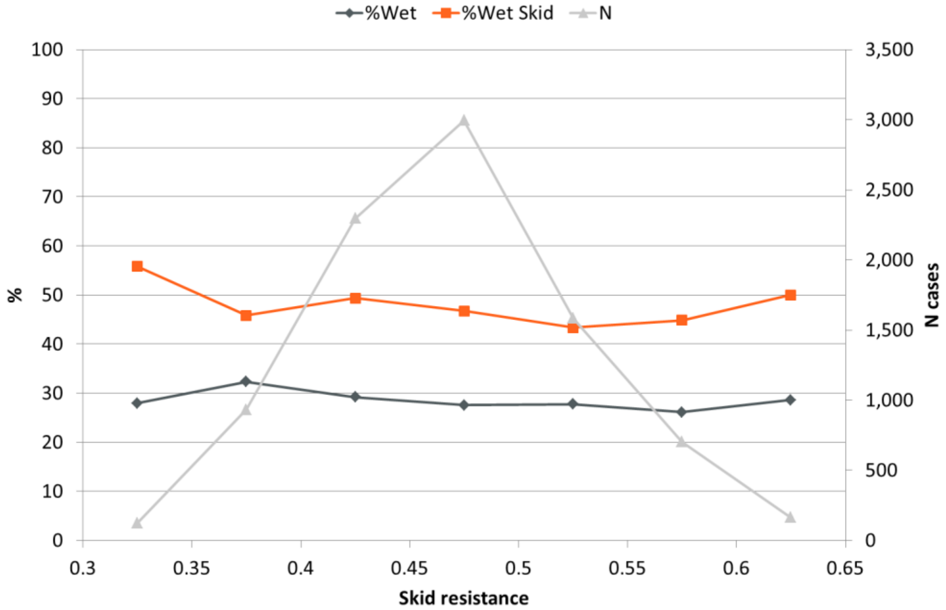
Figure 4: Collision risk by skid resistance for site category A



For all collisions on motorways, there appears to be a weak trend for decreasing collision risk as the skid resistance increases. Similarly to all collisions, both wet and wet skid collision risk decrease as skid resistance increases.

Around 30% of collisions are in wet conditions and around 30-50% of these wet collisions are classified as wet-skid collisions i.e. involve at least one vehicle skidding or jack-knifing (see Figure 5). The light grey ‘N’ shows the number of sections with each level of skid resistance included in the analysis.

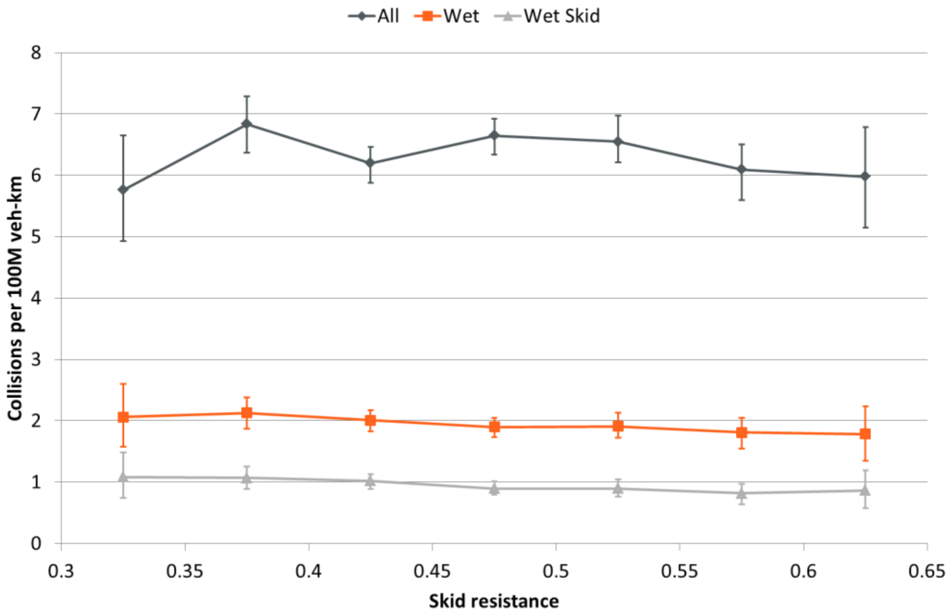
Figure 5: Collision ratios and numbers by skid resistance for site category A



The chart shows that the proportion of collisions which are wet collisions increases slightly at lower levels of skid resistance. A similar trend is evident when examining the proportion of wet collisions which are skidding collisions: at lower levels of skid resistance a greater proportion of skidding is recorded in wet conditions.

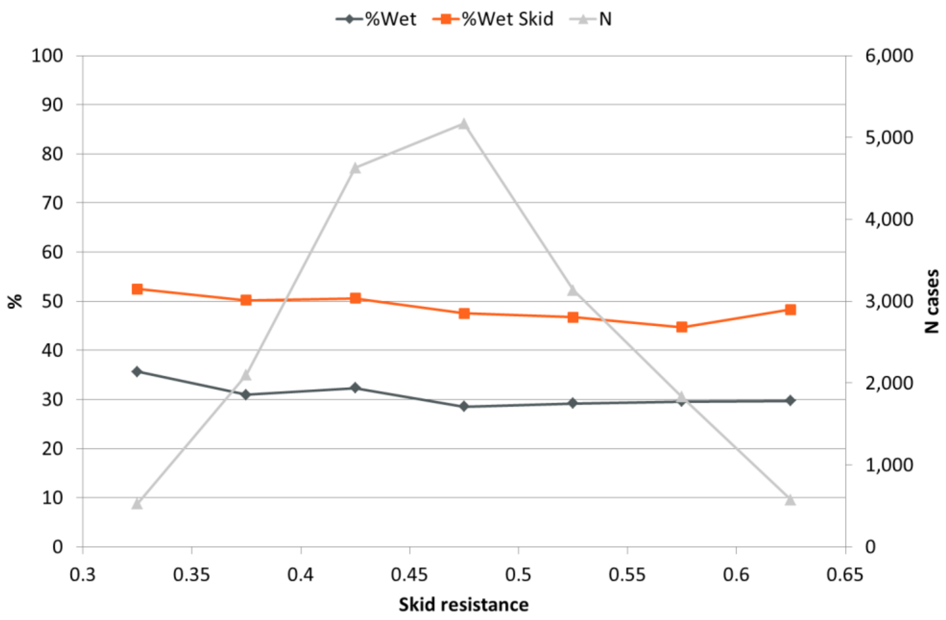
Figure 6 shows the collision risk, wet collision risk and wet skid risk for site category B (non-event carriageway with one-way traffic).

Figure 6: Collision risk by skid resistance for site category B



Similarly to motorways, a weak decreasing trend in collision risk may be observed for non-event carriageways with one way traffic as skid resistance increases from 0.40 to 0.65. The lower collision risk associated with skid resistance below 0.40 is not inconsistent with this trend when the larger the error bars are taken into account. However, the more substantial increase in collision risk that was observed in the previous work at skid resistance below 0.4 (see Appendix A) is not reproduced in this analysis.

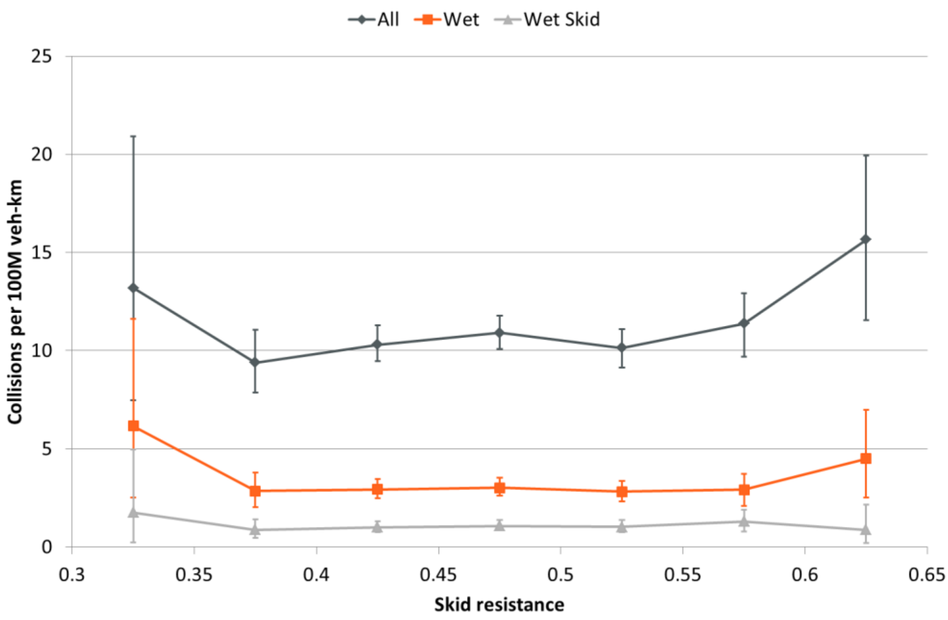
Figure 7: Collision ratios and numbers by skid resistance for site category B



Similarly to motorways, the proportion of wet collisions and wet skid collisions are slightly higher at lower levels of skid resistance. Appendix A shows that this trend has been reduced compared to the previous work.

Figure 8 shows the collision risk, wet collision risk and wet skid risk for site category C (non-event carriageway with two-way traffic).

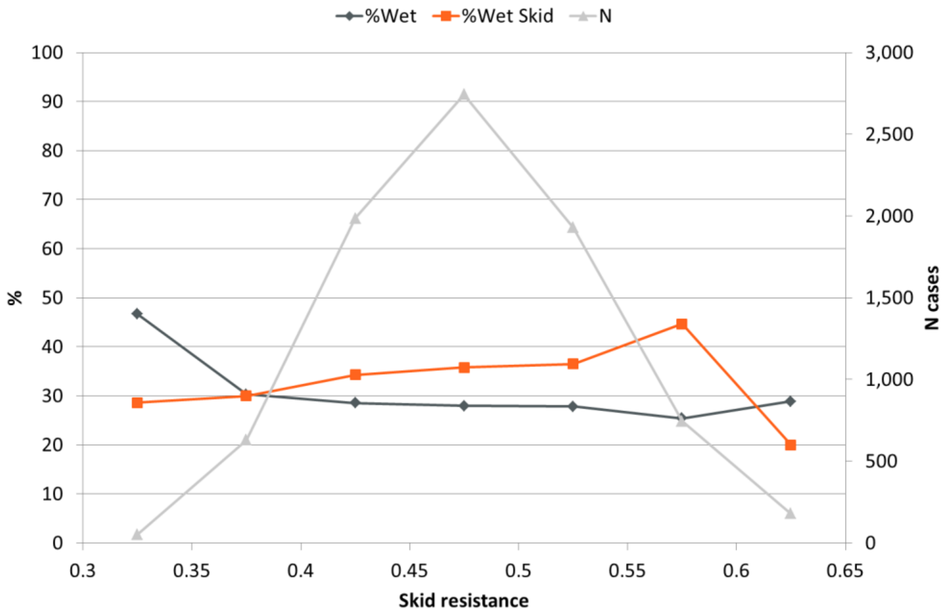
Figure 8: Collision risk by skid resistance for site category C



The variation in mean collision risk for non-event carriageways with two-way traffic does not appear to exhibit the same trend to that seen for motorways and non-event carriageways with one-way traffic. Although a weak trend, as skid resistance increases the collision risk also appears to increase.

This trend is in the opposite direction to that seen for motorways and carriageways with one-way traffic above, and to the relatively strong trend observed previously for single carriageway non-event sections (the equivalent site category in the previous work). Compared with the previous work, the elevated collision risk on sections with lower skid resistance has been eliminated.

Figure 9: Collision ratios and numbers by skid resistance for site category C



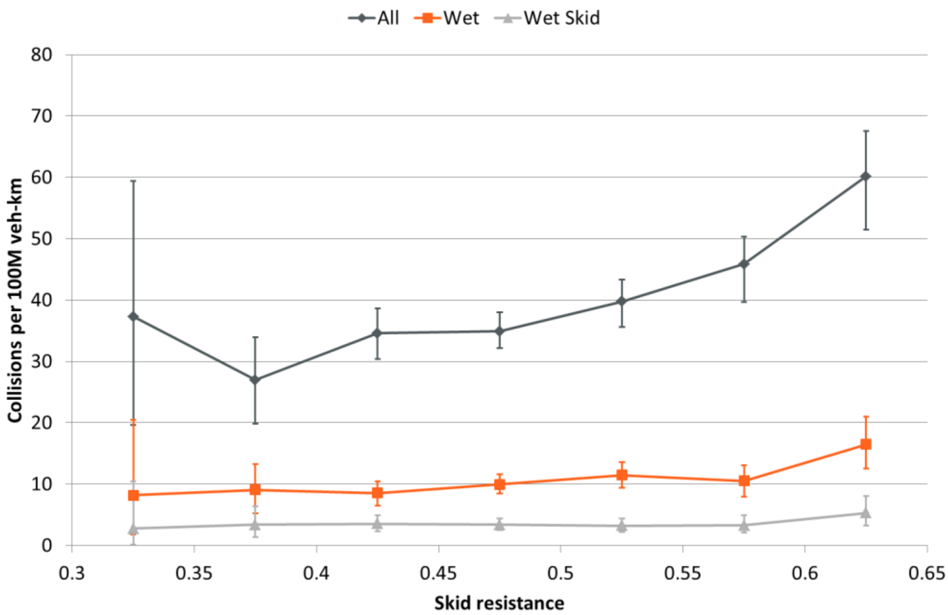
The proportion of collisions which occur in wet conditions shows a slight decreasing trend as skid resistance increases, which matches with the trends seen for motorways and carriageways with one-way traffic. However, in contrast to the trend for motorways and carriageways with one-way traffic, as skid resistance increases the proportion of wet collisions which are wet skid collisions increases; it is not clear what is driving this trend. However, Table 4 shows that the overall proportion of wet collisions which involve skidding for category C (35%) is similar to categories Q, K and R, whereas the proportions for the other categories, including A and B, are all close to 50%.

3.2 Approaches to junctions and pedestrian crossings (Q and K)

Figure 10 shows the collision risk by skid resistance for site category Q (approaches to junctions and roundabouts) and K (pedestrian crossings and other high risk situations). As discussed in Section 2.6, these site categories have been combined since there is only a relatively small length of the network classified as category K.

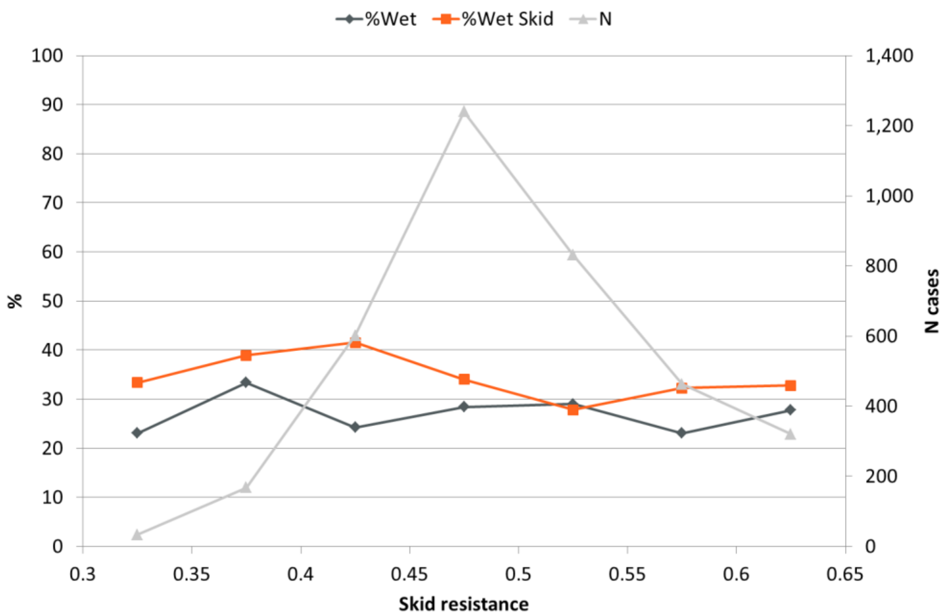
Note that these results cannot be compared directly to those from the previous study since in that study results were split into minor and major junctions whereas these are now combined (in line with HD28/04).

Figure 10: Collision risk by skid resistance for site category Q and K combined



The chart shows that as skid resistance at these sites increases, so does the collision risk. Ignoring the data point with the lowest skid resistance, which is associated with a small number of cases, the trend appears strong, particularly for all collisions.

Figure 11: Collision ratios and numbers by skid resistance for site category Q and K combined



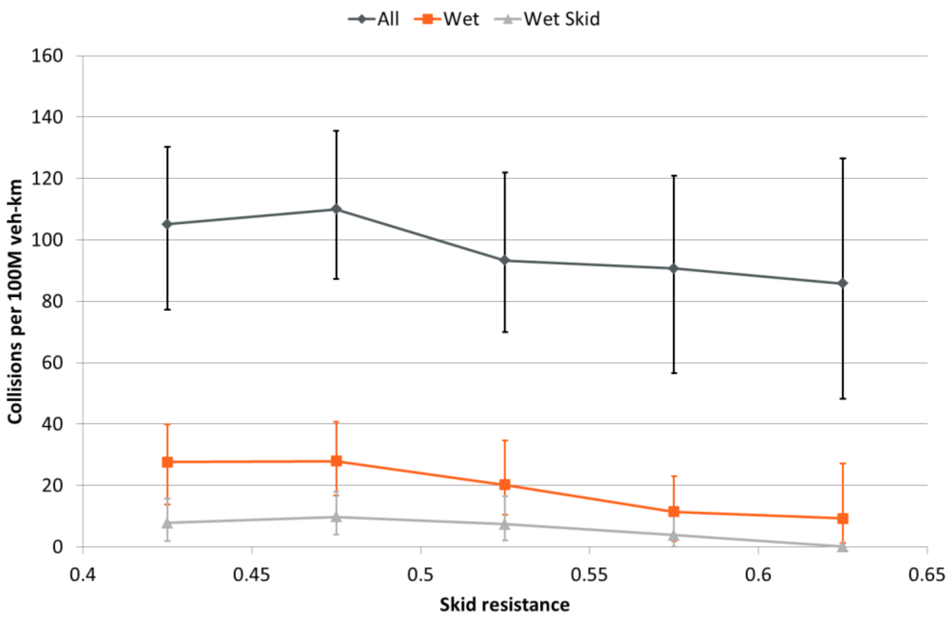
The proportion of collisions recorded as wet (%Wet) appears to fluctuate with no particular trend across the range of skid resistance. For the proportion of collisions recorded as wet skid (%Wet Skid) the percentage is generally a little higher to the left of the chart (lower skid resistance) than on the right.

3.3 Roundabouts (R)

Figure 12 shows how collision risk varies by skid resistance at roundabouts. Note that as discussed in Section 2.6, only a small proportion of the length of network classified as roundabouts has traffic data available so caution should be applied when interpreting these results as they are less robust than for the other site categories.

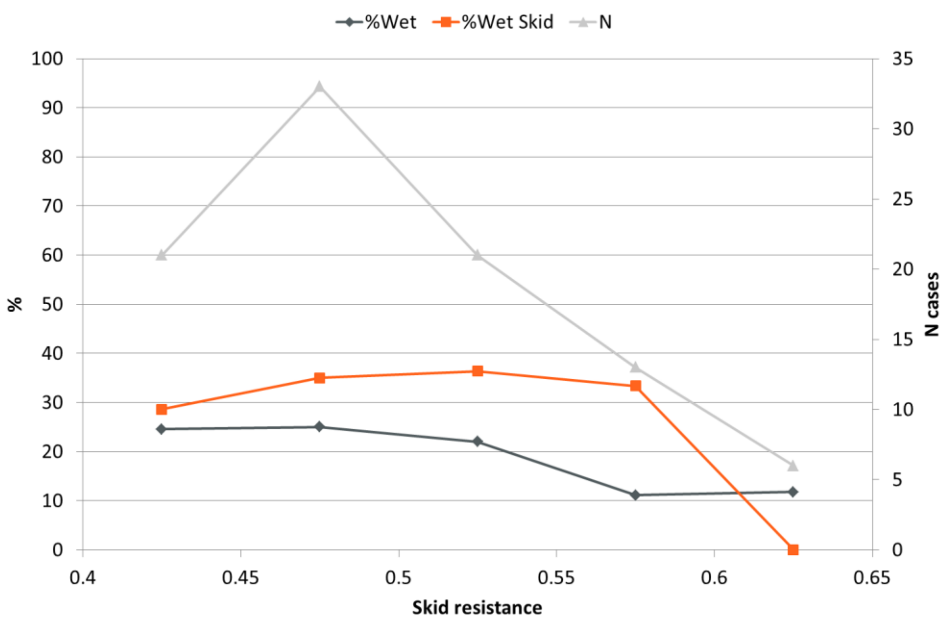
Note there was very little roundabout network with skid resistance of less than 0.4 so the first two categories have been excluded from this analysis.

Figure 12: Collision risk by skid resistance for site category R



Generally, there appears to be a decreasing trend for collision risk, wet collision risk and wet skid collision risk as skid resistance on roundabout sections increases from 0.45 to 0.60.

Figure 13: Collision ratios and numbers by skid resistance for site category R

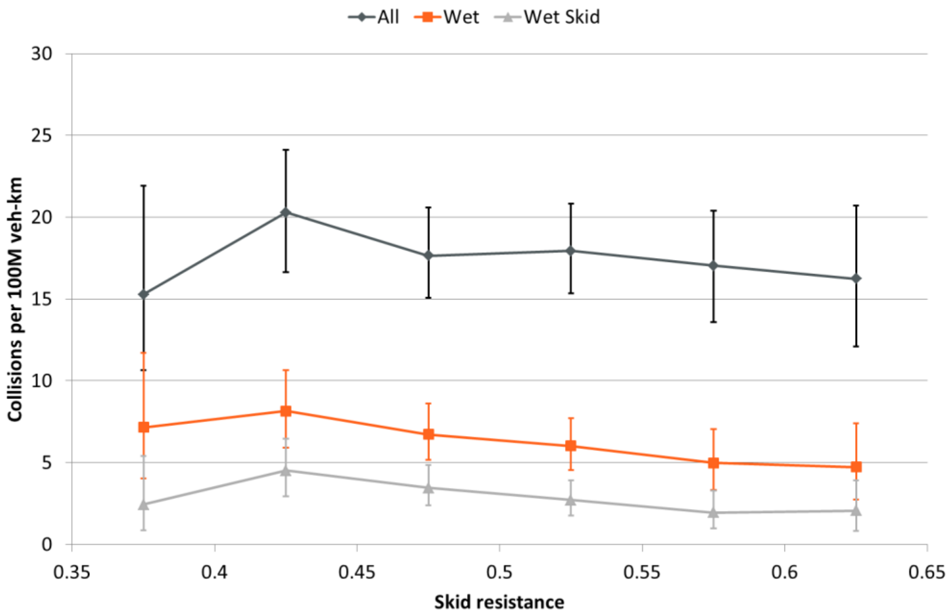


Over the same range of skid resistance (0.45 to 0.60) the proportion of collisions which are wet collisions decreases but the slight upwards trend in wet skid collisions; this may not be robust given the small total number of wet skid collisions on roundabouts (16). Note there were no wet skid collisions at the highest level of skid resistance.

3.4 Bends (S1 and S2)

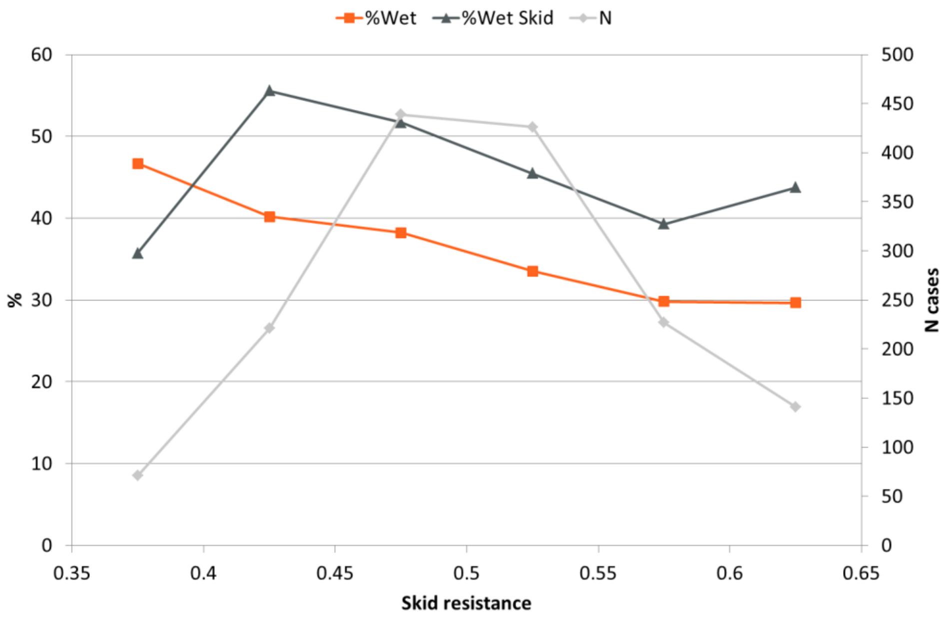
As discussed in Section 2.6, categories S1 and S2 have been combined since the length of sections and number of collisions on each was relatively small. Figure 14 shows how the collision risk for these categories changes with skid resistance. Note there was very little network with skid resistance of less than 0.35 so the first skid resistance category has been excluded from this analysis.

Figure 14: Collision risk by skid resistance for site category S1 and S2 combined



Collision risk, wet collision risk and wet skid collision risk are all shown to decrease as skid resistance increases from 0.45 to 0.65. Below these values, the collision risk is based on a smaller number of sections (Figure 15) and hence should be treated with caution.

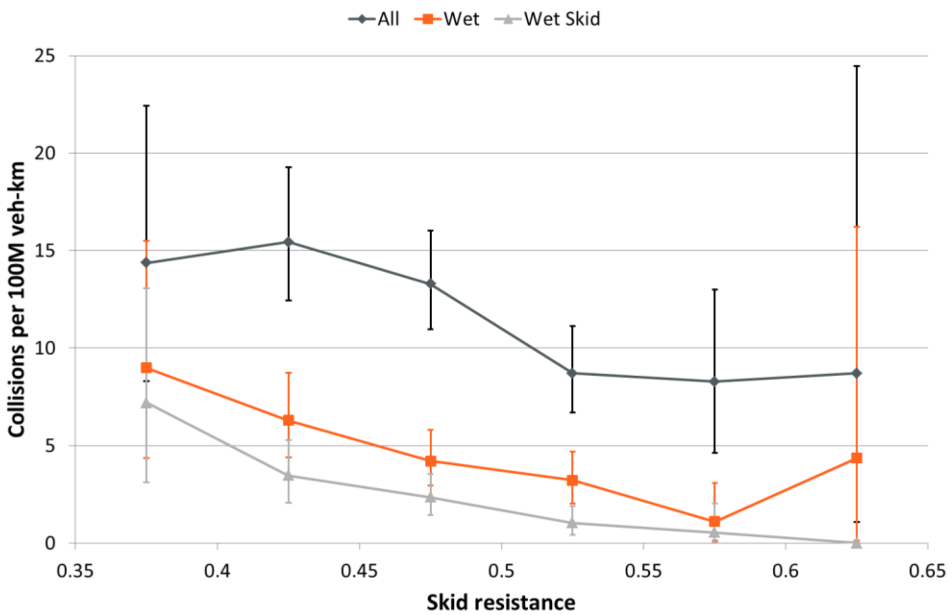
Figure 15: Collision ratios and numbers by skid resistance for site category S1 and S2 combined



3.5 Gradients (G1 and G2)

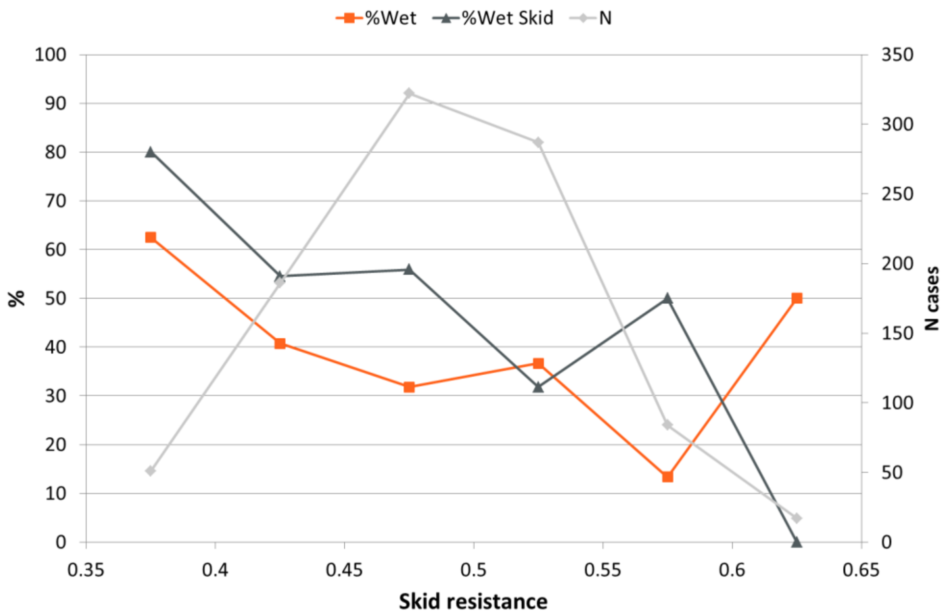
Due to the short length of network classified as G2 (gradient ≥10% longer than 50m) this site category has been combined with G1 (gradient 5-10% longer than 50m). Figure 16 shows the collision risk for these categories combined.

Figure 16: Collision risk by skid resistance for site category G1 and G2 combined



In common with many of the trends seen for the other site categories, as skid resistance on gradients increases the collision risk decreases.

Figure 17: Collision ratios and numbers by skid resistance for site category G1 and G2 combined



At lower levels of skid resistance, a higher proportion of collisions were wet collisions and a higher proportion of the wet collisions involved skidding.

4 Modelling

This section presents results of the statistical modelling. Models have been developed for each of the site categories (A, B, C, Q and K combined, G1 and G2 combined, S1 and S2 combined). Due to availability of traffic, road geometry and surface condition data it was not possible to develop models for category R (roundabouts).

4.1 Approach

A multivariate regression technique known as Generalised Linear Modelling was used to investigate the relationship between collisions and a number of variables including skid resistance (where this was identified as being an important predictor of collisions).

For the purposes of these models, the collisions have been assumed to follow a negative binomial distribution (a common distribution used for modelling count data such as accidents). The models developed are of the form:

$$Collisions = Length\ .Flow^{\alpha} \exp(\beta_0 + \beta_1 x_1 + \cdots + \beta_n x_n)$$

where $\alpha, \beta_0, \beta_1, \ldots, \beta_n$ are coefficients estimated by the model and $x_1, \ldots, x_n$ are variables which are identified as being significant predictors of the number of collisions. A number of variables were tested for inclusion in the model[6]:

- Average skid resistance
- Average rut depth
- Average texture depth
- Curvature = 1/radius (based on the tightest absolute radius for each section)
- Gradient; each section was classified into uphill (maximum gradient >5), flat (maximum gradient between 5 and -5) or downhill (maximum gradient <-5)
- Average crossfall

The base model was developed which included an intercept term (β_0) and the length of the section as an offset (i.e. the coefficient associated with this term was set to 1). This decision was made since, in line with the previous research, the section lengths were nearly constant (approximately 500m for motorway sections and 200m for all other site categories) so the effect of length could not be modelled.

Each explanatory variable was then added to the base model in turn and was assessed to determine whether including that variable reduced the unexplained variance in the number of collisions by a significant amount. The variable which improved the model the most was added at each stage. This process was repeated until no further variables were deemed to improve the model fit significantly.

[6] Note that in addition to the missing traffic data (seen in Table 2), for each site category some geometry and surface characteristics data are also missing. The models developed here only include those sections with complete flow data and complete data for all the significant predictors. The number of sections (N) included in each model is shown in Appendix B.

Separate models were developed for ‘all collisions’ and collisions defined as ‘wet collisions’, since skid resistance in particular is expected to have a greater influence on wet collisions than those in dry conditions. The significant predictors in each model are compared to determine if these models suggest similar relationships between these variables and the number of collisions.

The results of the final models for each site category are presented in the following sections. Where possible, comparisons are made to the results from the previous study. However, caution should be applied with these comparisons since there are likely to be differences in the processing of the raw data; for example, in the way each 200m or 500m section was defined.

The proportion of variance explained by each of the models is also estimated: a value of 100% would indicate that the model perfectly predicts the number of collisions in a four year period on each (200m or 500m) section of road. The values for the models presented in this report are in the range of 2% to 16%, i.e. there is a large amount of variance in the number of collisions which cannot be explained using the variables available for this analysis. This may be partly due to the nature of the analysis: it is necessary to disaggregate the road network to short lengths to cater for localised changes in surface condition and, as collisions are rare events, there is a high degree of variability in the number of collisions occurring in any one analysis length.

As a result, caution should be applied when interpreting these models since, although the significant variables indicate there may be a relationship between collision numbers and the variable of interest, there may be other factors (for example, weather, traffic composition, vehicle speeds etc.) which have a larger influence on the collision numbers and have not been accounted for in this analysis. The results presented here can be used to give an indication of the direction of the relationship between the significant variables and collision numbers (for example to suggest that increasing skid resistance decreases the number of collisions), but not to predict the actual number of collisions expected on a given section.

The coefficients for each model are shown in Appendix B.

4.2 Motorway non-event (A)

For all collisions, the following variables were identified as significant predictors of collision risk on motorways: crossfall, texture depth and skid resistance. The level of traffic (AADT) was also included in the model.

The coefficients for flow and crossfall are positive. This supports the assertion that as flow increases so do collisions and suggests that higher values of crossfall are associated with larger collision numbers.

In contrast, increasing the texture depth or skid resistance has the opposite effect on collisions; higher values of skid resistance (or texture depth) are associated with fewer collisions. This direction is as would be expected.

A similar model was also developed for wet collisions only; this model indicated that skid resistance and texture depth are significant predictors of wet collisions but, unlike for all collisions, crossfall was not selected. The pattern of coefficients was similar for the two models but the absolute value of the skid resistance coefficient was larger (-1.51 in the wet collision model compared to -0.80 in the all collisions model), suggesting that a change in skid resistance has a bigger impact on the change in the number of wet collisions than it does on the number in dry conditions.

The proportion of variance explained by these two models was 16% (all collisions) and 9% (wet collisions).

The previous work reported very different predictors of collision risk on motorways: skid resistance was not significant; neither was texture depth but curvature was found to be significant.

4.3 Non-event carriageway with one-way traffic (B)

For all collisions, texture depth was the only variable identified as a significant predictor of collision risk on carriageways with one-way traffic. The coefficient for texture suggests that higher values of texture depth are associated with fewer collisions. The level of traffic flow (AADT) was also included in the model.

A similar model was also developed for wet collisions only; this model indicated that rut depth is a significant predictor of wet collisions, but no other variables were identified as improving the fit of the model.

The proportion of variance explained by these two models was 6% (all collisions) and 4% (wet collisions).

The previous work suggested that for non-event carriageways with one-way traffic skid resistance, texture depth and curvature were amongst the variables found to be significant predictors of collision risk.

4.4 Non-event carriageway with two-way traffic (C)

Similarly to the previous work, the model using all collisions suggests that on carriageways with two-way traffic texture depth and curvature are important factors for predicting collision risk. However, unlike in the previous work, skidding resistance was not identified as a significant predictor.

This finding was also supported by the model using only wet collisions which did not identify skidding resistance as a significant predictor.

The proportion of variance explained by these two models was 5% (all collisions) and 2% (wet collisions).

4.5 Approaches to junctions and pedestrian crossings (Q and K)

Category Q (approaches to junctions and roundabouts) and K (approaches to pedestrian crossings and other high risk situations) were separated in the previous work and skidding resistance was found to be a significant predictor of collision risk in both models. In this analysis, skid resistance was also found to be significant (in both models for all collisions and wet collisions only). Texture and crossfall (and rut, for the all collisions model) were also significant.

In line with the findings presented in Section 3.2, the coefficient for skid resistance is positive which suggests that as skid resistance increases, the number of collisions increases. The pattern of coefficients was similar for the two models but the skid resistance coefficient was larger in the wet collisions model (2.25 in the wet collision model compared to 1.95 in the all collisions model), suggesting that a change in skid resistance has a bigger impact on the change in the number of wet collisions than it does on the number in dry conditions.

The proportion of variance explained by these two models was 5% (all collisions) and 3% (wet collisions).

4.6 Bends (S1 and S2)

For the all collisions model, texture was identified as a significant predictor but skid resistance was not. In contrast, the wet collisions model suggests that skid resistance was significant and negative (as skid resistance increases, collisions decrease).

In the previous study, skid resistance was not identified as significant in the model for bends, but the curvature of the road was significant in the models for motorways, non-event carriageways with one and two-way traffic, suggesting that the amount of curvature is important for collision risk.

The proportion of variance explained by these two models was 7% (all collisions) and 4% (wet collisions).

4.7 Gradients (G1 and G2)

For both models, the skid resistance and magnitude of the gradient significantly influence the number of collisions. The coefficient for skid resistance is negative so, as skid resistance increases, the number of collisions decreases. This matches with the trend seen for gradients 5-10%[7] seen in the previous study.

The proportion of variance explained by these two models was 8% (all collisions) and 11% (wet collisions).

4.8 General observations from the modelling

In addition to the generally low proportion of the variance explained (Section 4.1), the collision models for the different site categories exhibit the following features and trends:

- Traffic flow features as an explanatory variable in all of the models and, in most cases, it was the first variable selected i.e. it reduced the unexplained variance in the model the most. The exceptions, where other variables were selected before AADT, were category Q & K (junctions and pedestrian crossings) and S1 & S2 (bends, but for the wet collision model only).
- Skid resistance and / or texture depth feature consistently as explanatory variables for many of the site categories. In the models for all collisions, texture depth is more

[7] Gradients >10% were not studied in detail in the previous study due to few data points for this category. For the purposes of the analysis presented in this report, these categories have been combined.

commonly selected than skid resistance and, if both feature in the model, texture depth is selected before skid resistance. The reverse is true in the models for wet collisions: skid resistance is selected more often, and always before texture depth.

- The importance of skid resistance in the models, i.e. how strongly changes in skid resistance influence collision risk (as judged by the model coefficients) increases in the following order:
  - Non-event categories B and C (not a significant predictor of collision risk)
  - Motorway category A
  - Bend category S1 & S2 and Junctions category Q & K (although for junctions the trend goes in the opposite direction)
  - Gradient category G1 & G2 (largest coefficient suggesting the strongest relationship)

  A similar order is observed for texture depth (except the variable is significant for non-event categories B and C, but not for gradient category G1 & G2).
- By comparing the model coefficients it is possible to provide a comparison in the strength of these trends. In the model for wet collisions, over the working range of skid resistance (say 0.6 decreasing to 0.3 units of sideway force coefficient[8]) and assuming all other variables remain constant, the average collision risk increases by nearly 60% for motorways, more than doubles for bends and multiplies by nearly 7 for gradients. Over the same range, the collision risk for junctions and pedestrian crossings reduces by half. (This comparison is indicative only: as noted above, the majority of the variability in collision risk for individual sections is superimposed on these general trends and is unexplained by these models. As a result, it is not considered robust to use these to predict reductions in collision numbers.)
- Similarly, the model for all collisions suggests that over the working range of texture depth (say 1.2mm decreasing to 0.3mm), the average collision risk increases by 10 to 30% for non-event categories A-C, increases by 60% for junctions and pedestrian crossings and doubles for bends.

[8] For illustrative purposes only – different ranges of skid resistance apply for these different categories in practice.

5 Summary and conclusions

This work used the same methodology as a previous analysis, carried out prior to the introduction of the 2004 skid resistance Standard, and a number of differences are noted in the results. Section 1.2 noted that sizeable reductions have occurred in casualty numbers and rates on the Strategic Road Network during the period between the two studies. These could be a result of changes to the road network (in particular the de-trunking since the previous study and more recent initiatives such as Smart motorways), to surfacing materials and road condition, to vehicle safety and crashworthiness and/or to overall traffic flows.

The following observations can be made in relation to skid resistance and collision risk for the site categories into which the road network is divided for the purpose of the Standard (Section 1.1).

5.1 Non-event categories (A, B and C)

For the non-event site categories, the results of this study show significant differences compared with the previous work. The previous work showed:

i) Overall collision risk increases in the order motorway (category A) < non-event carriageway with one-way traffic (category B) < non-event carriageway with two-way traffic (category C).

ii) The influence of skid resistance on the level of risk increases in same order.

From this new analysis, point (i) still holds true. The number of collisions observed per vehicle km travelled is ranked in the same order as in the previous work, and at a broadly consistent level.

Regarding point (ii), the influence of skid resistance on collision risk follows a similar, although weak, trend for motorways as seen in the previous work. For the other non-event categories, where previously a somewhat stronger trend was observed, this affect has now been reduced or eliminated, although a small increase is still seen in the proportion of collisions that occur in wet conditions on sections with lower skid resistance.

Consistent with the above, in the modelling for categories B and C, skid resistance was not a significant variable for either all collisions or wet collisions. For motorways, texture depth was a more important variable than skid resistance in the model for all collisions; texture depth is also significant in the all collisions models for categories B and C (unlike skid resistance, which is not). The importance of texture depth is consistent with long standing observations that a disproportionate number of collisions are recorded on roads with low texture depth than would be expected given their length, and that this affects both wet and dry conditions (Roe, Webster, & West, 1991).

In contrast, skid resistance does appear to be more important than texture depth in the model for wet collisions on motorways. To compare the relative magnitude of these effects over the working ranges of skid resistance and texture depth: the average risk of all collisions is 10-30% higher on lengths with low texture depths in categories A-C (Section 4.8) whereas on a realistic range of skid resistance on motorways (say 0.45 decreasing to 0.3) the models suggest a 25% increase in *wet* conditions or just over a 10% increase when considering the overall risk.

It is not possible to tell from this analysis whether the changes result from improvements in the safety of the road system that have reduced the influence of sections with low skid resistance, or from de-trunking of the sections where the influence of skid resistance was more important, or more generally from improvements to the vehicle fleet. In any case, the current application of the Standard seems to be providing an effective level of skid resistance, with little evidence that non-event sections with lower skid resistance exhibit markedly higher levels of risk. However, the role of texture depth seems to be at least as important as skid resistance, for all of the non-event categories, in dry as well as wet conditions. This would benefit from further investigation.

5.2 Approaches to junctions and pedestrian crossings (Q and K)

Junctions and pedestrian crossings exhibit a strong trend with increasing skid resistance, but it is for collision risk to *increase* rather than *decrease*. This was observed both in the exploratory analysis and the modelling.

The 2004 Standard introduced a new category for junctions, with a wider range of Investigatory Level than other categories. The trends observed in this work suggest that higher risk sites are correctly being provided with higher skid resistance, but that this strategy is either ineffective (i.e. has no impact on the level of risk), or does reduce risk but not to background levels. The proportion of collisions in wet conditions is close to being flat across the range of skid resistance; for wet collisions the proportion that involved skidding shows a modest increase for lengths with lower skid resistance (Figure 11). This final observation suggests against reducing the skid resistance levels for junctions and pedestrian crossings, but it is unclear that further improvements in skid resistance would provide additional benefits.

5.3 Roundabouts (R)

The exploratory analysis shows a decreasing trend for collision risk, wet collision risk and wet skid collision risk as skid resistance on roundabout sections increases from 0.45 (the current default IL) to 0.60. Considering all collisions, the average increase in risk for sections with lower skid resistance is just over 20% and the proportion occurring in wet conditions doubles. These results should be treated with caution in case the sample is biased by the nature of the roundabouts for which traffic data were available. Also, it has not been possible to develop statistical models to verify the importance of skid resistance due to the lack of traffic data. (Geometry, texture depth and other road condition parameters are also unavailable for roundabouts, which are not included within routine surveys for these parameters.)

From Table 4 a notably lower proportion of collisions on roundabouts occur in wet conditions than for other site categories, and in the data set used for this analysis these collisions were associated with zero fatal injuries and a lower proportion of fatal/serious injury than the other categories (Table 3). This is likely to be due to the efficacy of roundabout design in reducing conflicts between road users. However, the exploratory analysis points to an increase in risk associated with skid resistance below 0.5, whereas the current default IL in the Standard is 0.45.

Consideration should therefore be given to increasing the IL for this site category. The current specifications for surfacing materials (Highways England, 2012) suggest that an IL of 0.50 could be achieved using natural aggregate rather than high friction surfacing materials which are problematic due to their low life expectancy on roundabouts. This should perhaps be verified before increasing the IL. Also, it would be desirable to investigate the nature of the roundabouts with traffic data available in this work, to check for potential bias, and to develop and alternative methodology for examining trends on a more representative sample if necessary.

5.4 Bends (S1 and S2)

On first sight it is puzzling that skid resistance is not significant in the model for all collisions for bends since the exploratory analysis suggests collision risk decreases on sites with higher skid resistance. However, in Figure 14 the data point for sections with skid resistance 0.4-0.45 drives much of the impression of the trend for all collisions. The trends in the exploratory analysis are clearer for collisions in wet conditions, and for wet collisions involving skidding, for which the collision rates decrease continuously as the skid resistance increases.

An overall 35% of collisions on bends occur in wet conditions, similar to gradients and higher than the other categories (Table 4). The percentages of wet collisions and wet collisions involving skidding also drop as the skid resistance increases (a trend that is not observed as strongly for other sites categories). Skid resistance is significant in the model for wet collisions: on average the risk of collisions in wet conditions is 30% higher at a skid resistance of 0.45 (the current IL for roads with one-way traffic which can be met with natural aggregate up to 5000 CVD[9]) than for 0.55 (which requires high friction surfacing materials in almost all cases). As for roundabouts, consideration should be given to the feasibility of increasing the IL.

5.5 Gradients (G1 and G2)

The trends observed for this category are similar to those for bends: however, the downward trends for wet collisions and wet collisions involving skidding are more pronounced for gradients and are now joined by a marked downward trend affecting all collisions. Skid resistance is significant in the models for both all collisions (this was not the case for bends) and for wet collisions (as for bends) and with a larger coefficient, which indicates a stronger effect: this time the average collision risk increases by 50% for all collisions and 90% for wet collisions as skid resistance decreases from 0.55 to 0.45. The proportions of wet and wet skidding collisions are similarly high in comparison to the other site categories (Table 4) and are strongly influenced by changes in skid resistance.

5.6 Other observations

Texture depth appears in all the models for all collisions with the exception of the gradients category. The model coefficients increase in the order: non-event categories A-C < junction

[9] Commercial vehicles per lane per day at design life (Highways England, 2012)

< bend. Traditionally, texture depth has been required to limit the loss of grip on wet roads at high speeds (Roe, Parry, & Viner, 1998). However, as the texture depth seems to be either not significant or less significant than skid resistance in the models for wet collisions, this property doesn't seem to be only associated with preventing vehicles skidding on wet roads. It may be more generally associated with an increased road surface friction in all conditions. In this case a more detailed analysis of the contribution of texture depth to collision risk, that considers the different nature of the texture depth provided by different surfacing types, should be considered.

Traffic flow is always significant as an explanatory variable in the modelling. Other things being equal, there will be greater potential to reduce the number of injuries on sections that carry higher traffic and this should be reflected in prioritisation of treatments if budgets are fixed.

Other than skid resistance and texture depth, none of the other geometry and road condition variables appeared consistently in the models for collision risk: crossfall was selected in the all collisions model for motorways and for both models for junctions, curvature was selected in the all collisions model for non-event sections with 2-way traffic and rut depth was selected in the wet collisions model for non-event sections with 1-way traffic.

The statistical models explain only a low proportion of the overall variation in collision risk observed between the lengths in the dataset. This may be a result of the way the network has been divided into short lengths to cater for local changes in surface condition (Section 4.1). Typically 4-10% of the variation is explained; slightly higher for the models on motorways, possibly due to the longer analysis length used for this category. This means that although the average trends are relevant to determining an appropriate strategy for managing skid resistance, it is not possible to be confident in predicting the actual numbers of collisions expected on a given section.

5.7 Recommendations

The following recommendations are made as a result of this work:

1. For bends and gradients the skid resistance exhibits a significant influence on collision risk. While this study does not demonstrate a causal link, sections with higher skid resistance currently exhibit lower risk of collisions and fewer collisions in wet conditions. Treatments to these sites identified by the current Standard should be prioritised.
2. In addition, providing higher levels of skid resistance for bends and gradients may result in safety improvements. This could be validated through a 'before and after' study of the effect of current or past interventions. However, providing higher skid resistance on these types of site is challenging due to the high degree of polishing that is imparted by traffic. Any further work should therefore consider the practicality of achieving a cost effective and sustainable solution through enhanced skid resistance and other options for reducing risk, such as reduced the speed limits.
3. The situation is similar for roundabouts. Although their design is inherently safer (low fatalities and low incidence of skidding in wet conditions) the collision rates are high. The current study is limited by the lack of availability of traffic data, texture and

geometry data, which could potentially be addressed though analysing collision numbers (as opposed to rates). This approach could also be extended to slip roads, for which traffic data were mainly unavailable in this study.

4. No change is recommended to the ILs for non-event categories A-C. The trends with skid resistance are reduced in comparison to the previous work but the current Standard can be delivered easily with the materials available and there is some evidence of increasing risk at low skid resistance. Therefore a reduction in IL is not recommended. The results suggest that texture depth is at least as important as skid resistance on the non-event lengths. Investigation of the trends with texture, using a similar approach to the exploratory analysis for skid resistance (above). This should consider the effect of the different forms of surface texture provided by different surface types.
5. No change is recommended to the ILs for junctions (category Q) and pedestrian crossings (K). Whilst sites in these categories with higher skid resistance are associated with higher collision risk, it is possible that the elevated skid resistance is helping to mitigate the risk, even if it is not returning it to background levels. However, alternative interventions to reduce the source of the risk may be more effective than improving skid resistance.

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Appendix A Comparison to results from previous work

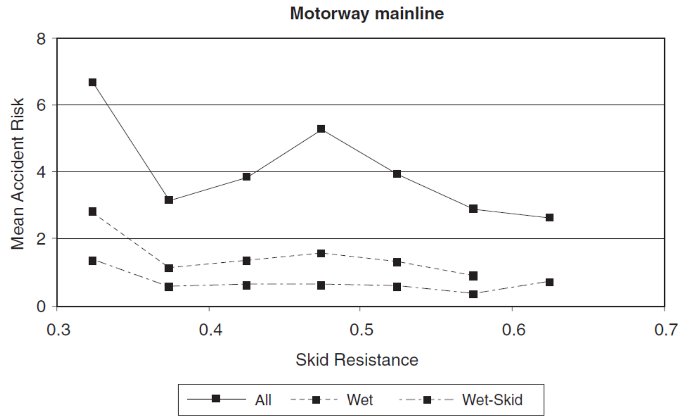
<table>
<tr><th>Site category</th><th>Results from previous study (Parry & Viner, 2005)</th><th>Results from this analysis</th><th>Comparison of results</th></tr>
<tr><td rowspan="2">Motorway non-event (A)</td><td>

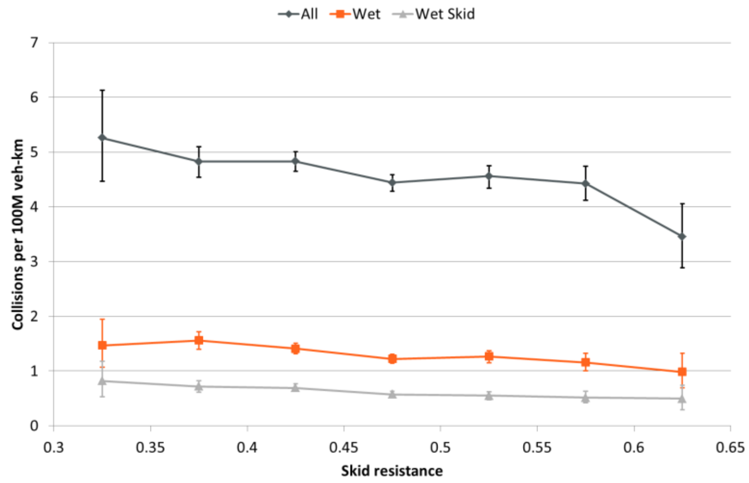
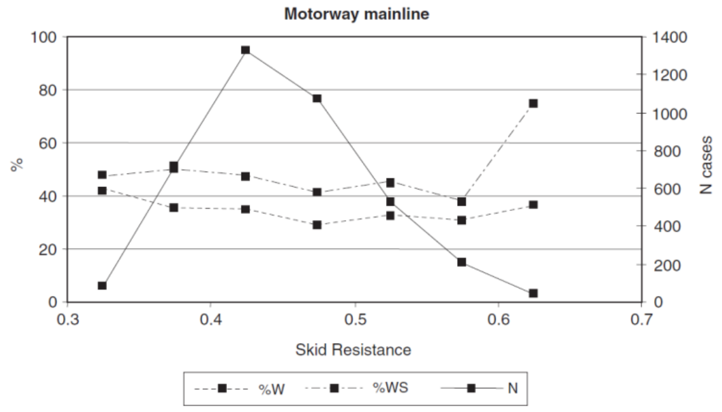
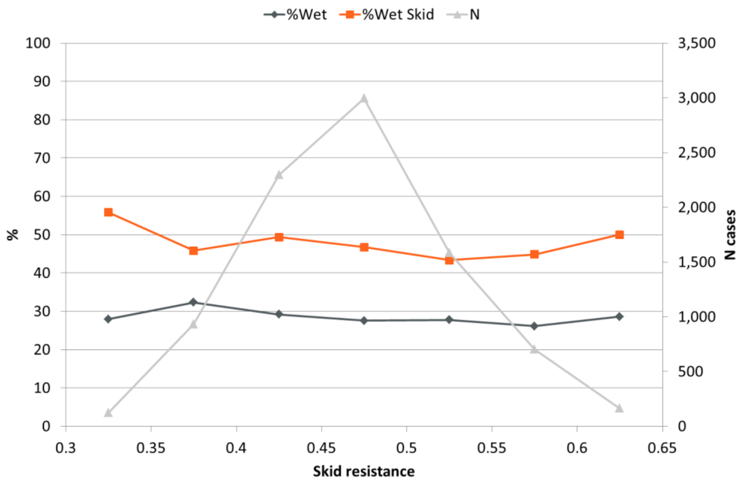
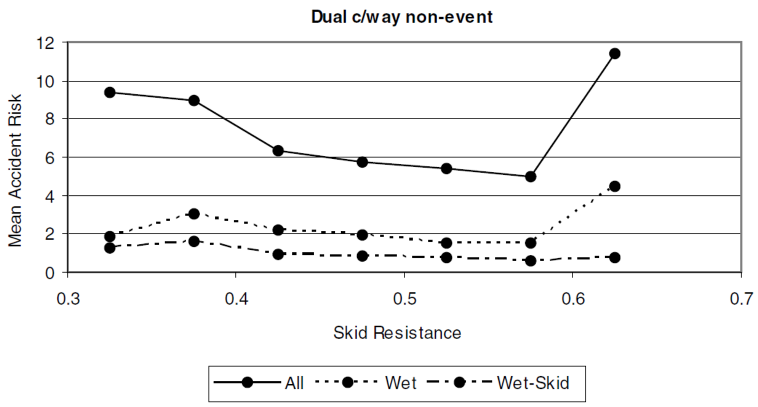
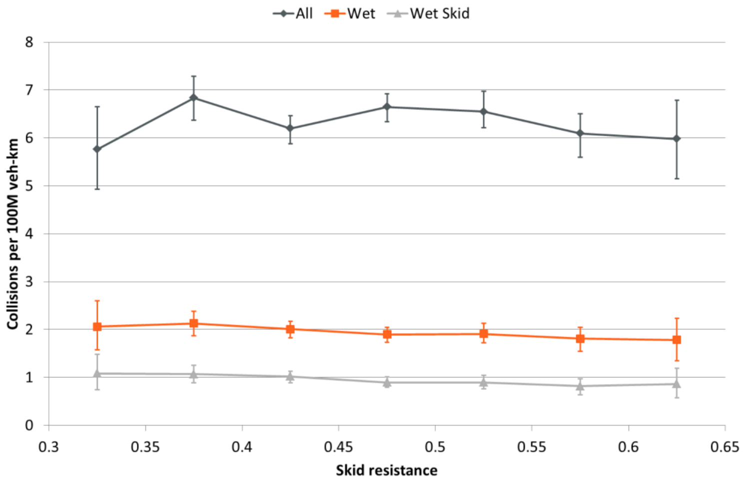
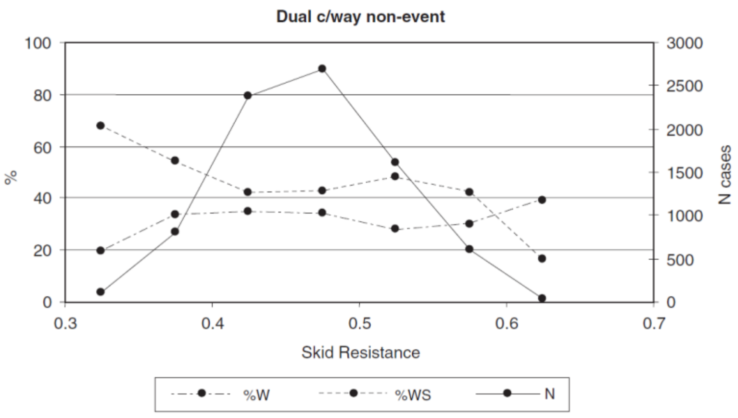
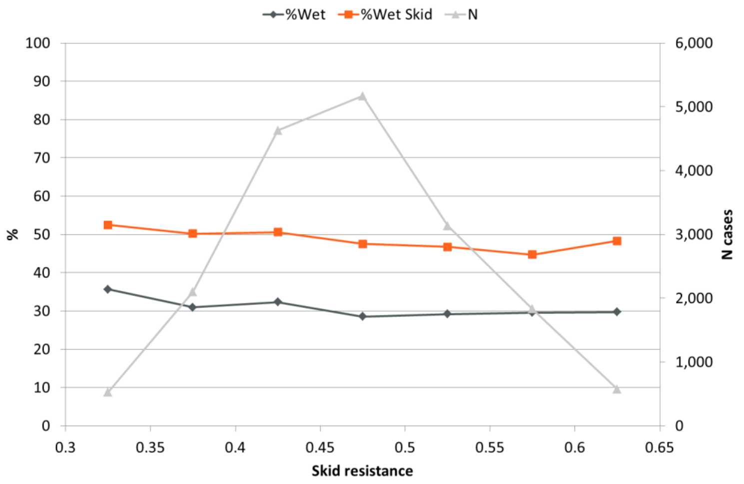
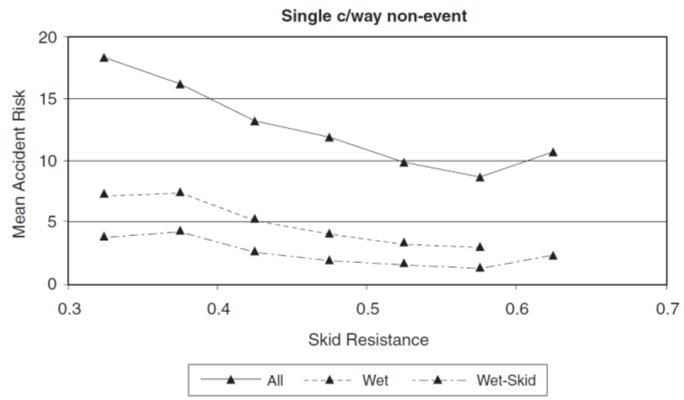
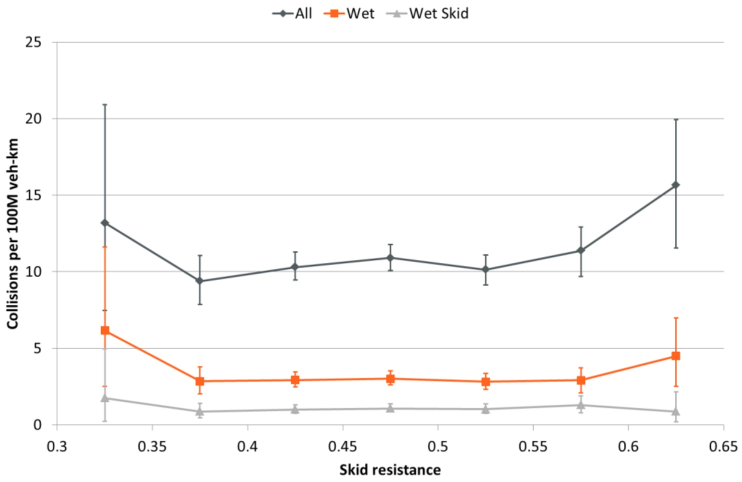
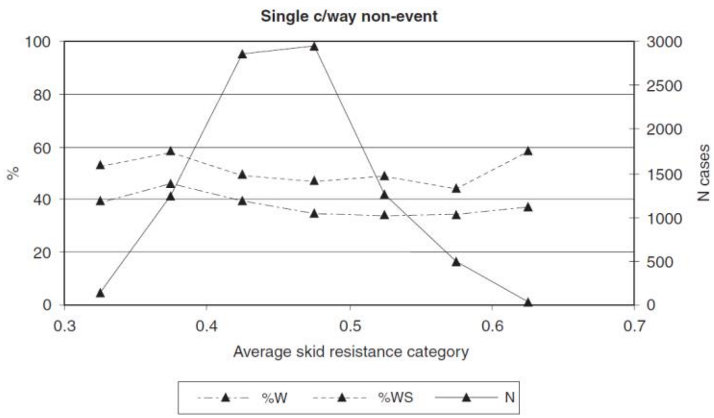
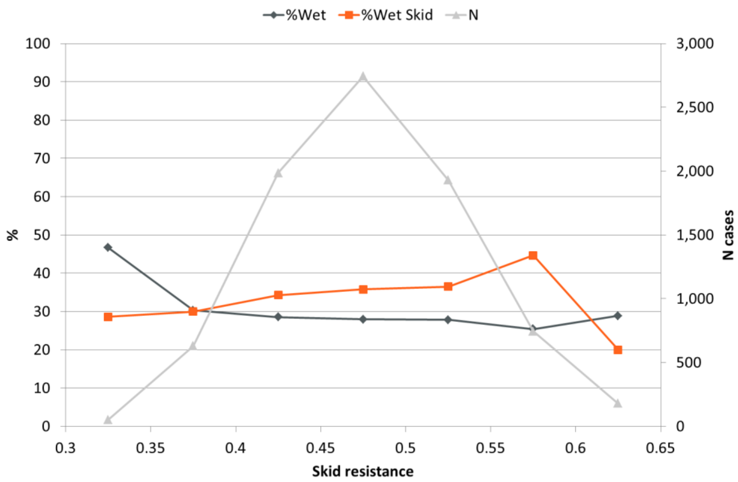
Figure 2 Mean accident risk by skid resistance for motorways</td><td>
</td><td>The shape of the trend (collision risk decreases as skid resistance increases) and the magnitude of collision risk is fairly comparable between the studies.</td></tr>
<tr><td>

Figure 3 Accident ratios and numbers by skid resistance for motorways</td><td>
</td><td>The proprtion of collisions which are wet collisions and the proportion of wet collisions which are wet skid collisions has changed very little between the two studies.</td></tr>
</table>

Site category	Results from previous study (Parry & Viner, 2005)	Results from this analysis	Comparison of results
Non-event carriageway with one-way traffic (B)	 **Figure 5** Mean accident risk by skid resistance for dual carriageways		In the previous study the trend in collision risk was generally downwards as skid resistance increased, with the exception of the last point which is probably as a result of small numbers. A similar but slightly weaker trend and was observed in this study.
	 **Figure 6** Accident ratios and numbers by skid resistance for dual carriageways		In the previous study, the trend in the proportion of wet collisions which resulted in a skid decreased as skid resistance increased; a weaker trend is evident in this study.

<table>
<tr><th>Site category</th><th>Results from previous study (Parry & Viner, 2005)</th><th>Results from this analysis</th><th>Comparison of results</th></tr>
<tr><td rowspan="2">Non-event carriageway with two-way traffic (C)</td><td>
Figure 7 Mean accident risk by skid resistance for single carriageways</td><td></td><td>The relatively strong relationship observed in the previous study has been replaced by a weak trend in the opposite direction. The collision risk is similar at higher levels of skid resistance, suggesting that the elevated risk at lower levels of skid resistance has been eliminated.</td></tr>
<tr><td>
Figure 8 Accident ratios and numbers by skid resistance for single carriageways</td><td></td><td>Compared to the previous study, a smaller proportion of collisions on carraigeways with two-way traffic were in wet conditions and a smaller proportion of these were wet skid collisions. The increasing proportions of wet and wet skid collisions previously seen at lower skid resistance are largely eliminated in this work.</td></tr>
</table>

Appendix B Model coefficients

This appendix presents the coefficients from the 'all collisions' and 'wet collision' models developed in Section 4. The order in which variables are shown in the tables below is the order in which they were selected for inclusion in the model (see Section 4.1). Most variables were included in the models as continuous variables but one (gradient) was included as a factor (with a number of different levels). Each model also included an intercept (constant) term.

For each continuous variable (X), one coefficient will be displayed. This coefficient can be interpreted as follows: for a one unit increase in X, the number of collisions will increase by a factor of $\exp(coef\ of\ X)$, all else held constant.

For the variable gradient (which was included as a factor with three levels: up, down and flat), one level is chosen as the reference level. In this case, 'flat' (i.e. with a gradient of between -5 and 5) was the reference level, and therefore the coefficient for sections of this type is set to zero. The coefficients for the other two groups are estimated relative to this reference group. Using an uphill gradient as an example, if the coefficient for uphill was 1, then this could be interpreted to mean that the expected number of collisions on an uphill section of road, all else held constant, was $\exp(1) = 2.7$ times that of a flat section of road.

B.1 Motorway non-event (A)

Table 5: Model coefficients for the motorway 'all collisions' model (N=8,807[10])

Variable	Coefficient	Standard error
Intercept	-19.80	0.43
Log(AADT)	1.20	0.03
Crossfall	0.02	0.01
Texture	-0.17	0.04
Skid resistance	-0.80	0.22

Proportion of variance explained by the model = 16%

Table 6: Model coefficients for the motorway 'wet collisions' model (N=8,807)

Variable	Coefficient	Standard error
Intercept	-20.53	0.73
Log(AADT)	1.19	0.06
Skid resistance	-1.51	0.37
Texture	-0.16	0.07

[10] N shows the number of sections with complete observations for all of the significant variables. This is the number of sections on which this model was run.

Proportion of variance explained by the model = 9%

B.2 Non-event carriageway with one-way traffic (B)

Table 7: Model coefficients for the non-event carriageway with one-way traffic 'all collisions' model (N=18,030)

Variable	Coefficient	Standard error
Intercept	-15.83	0.38
Log(AADT)	0.86	0.03
Texture	-0.10	0.04

Proportion of variance explained by the model = 6%

Table 8: Model coefficients for the non-event carriageway with one-way traffic 'wet collisions' model (N=18,030)

Variable	Coefficient	Standard error
Intercept	-16.92	0.59
Log(AADT)	0.85	0.05
Rut	-0.03	0.01

Proportion of variance explained by the model = 4%

B.3 Non-event carriageway with two-way traffic (C)

Table 9: Model coefficients for the non-event carriageway with two-way traffic 'all collisions' model (N=8,279)

Variable	Coefficient	Standard error
Intercept	-17.66	0.85
Log(AADT)	1.10	0.08
Texture	-0.31	0.08
Curvature	0.23	0.12

Proportion of variance explained by the model = 5%

Table 10: Model coefficients for the non-event carriageway with two-way traffic 'wet collisions' model (N=8,279)

Variable	Coefficient	Standard error
Intercept	-18.11	1.35
Log(AADT)	0.98	0.13

Proportion of variance explained by the model = 2%

B.4 Approaches to junctions and pedestrian crossings (Q and K)

Table 11: Model coefficients for the approaches to junctions and pedestrian crossings 'all collisions' model (N=3,834)

Variable	Coefficient	Standard error
Intercept	-10.66	0.75
Texture	-0.51	0.10
Log(AADT)	0.49	0.06
Skid resistance	1.95	0.47
Crossfall	-0.04	0.01
Rut	0.04	0.02

Proportion of variance explained by the model = 5%

Table 12: Model coefficients for the approaches to junctions and pedestrian crossings 'wet collisions' model (N=3,834)

Variable	Coefficient	Standard error
Intercept	-11.56	1.19
Skid resistance	2.25	0.74
Texture	-0.35	0.16
Log(AADT)	0.43	0.10
Crossfall	-0.05	0.02

Proportion of variance explained by the model = 3%

B.5 Bends (S1 and S2)

Table 13: Model coefficients for the bends 'all collisions' model (N=1,600)

Variable	Coefficient	Standard error
Intercept	-11.61	0.96
Log(AADT)	0.64	0.09
Texture	-0.76	0.19

Proportion of variance explained by the model = 7%

Table 14: Model coefficients for the bends 'wet collisions' model (N=1,602)

Variable	Coefficient	Standard error
Intercept	-11.80	1.43
Skid resistance	-2.56	1.12
Log(AADT)	0.59	0.12

Proportion of variance explained by the model = 4%

B.6 Gradients (G1 and G2)

Table 15: Model coefficients for the gradients 'all collisions' model (N=957)

Variable	Coefficient	Standard error
Intercept	-12.89	1.87
Log(AADT)	0.78	0.15
Skid resistance	-4.18	1.50
Gradient - downhill	0.52	0.19
Gradient - uphill	0.45	0.23

Proportion of variance explained by the model = 8%

Table 16: Model coefficients for the gradients 'wet collisions' model (N=957)

Variable	Coefficient	Standard error
Intercept	-15.39	2.84
Log(AADT)	0.99	0.23
Gradient - downhill	0.80	0.31
Gradient - uphill	0.81	0.36
Skid resistance	-6.36	2.32

Proportion of variance explained by the model = 11%

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