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Safety effects of traffic lane and shoulder widths on two-lane undivided rural roads: A matched case-control study from Norway

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ABSTRACT

This study estimates the effects of lane and shoulder widths on occurrence of head-on and single-vehicle accidents on rural two-lane undivided roads in Norway while considering the differences between winter and non-winter accidents and their severity levels. A matched case-control method was applied to calculate the odds ratios for lane and shoulder width categories, while controlling for the effects of AADT and adjusting for the effects of region, speed limit, segment length, share of long vehicles in AADT and horizontal alignment. The study used a sample of 71,999 roadway segments identified in GIS and 1886 related accidents recorded by the police in five-year period. The results suggest that it is relevant to consider winter and non-winter accidents as well as severe and slight accidents separately when studying the effects of lane and shoulder widths on the occurrence of head-on and single-vehicle accidents. When examining lane and shoulder widths for all related accidents, the lane widths 1.50–2.50 m and shoulder widths 0.50 – 0.75 m were relatively safer than other categories on Norwegian two-lane rural undivided roads.

1. Introduction

This study looks at the effects of cross-sectional elements' (lane and shoulder) widths on the occurrence of head-on and single-vehicle accidents on rural two-lane undivided roads in Norway. These roads comprise a major portion of the Norwegian public road network. Typically, this road type carries a higher level of accident risk than do other types of roads (Gooch et al., 2016). According to the Norwegian National Road Database NVDB, there were 8845 accidents recorded on these roads in Norway in the period 2014–2018, which represented 37% of all accidents in the country. Almost 75% (6608) of these accidents occurred on road segments, meaning sections of road that contain neither bridges, tunnels nor intersections. The majority (83%) of these segment-related accidents were categorised by police as single-vehicle (n = 3956) and head-on accidents (n = 1537). Most of them (85%) included a motorised vehicle, 14% involved a motorcycle and 1% a cyclist or pedestrian. Trucks have been frequently involved particularly in fatal head-on and single-vehicle accidents (Langeland and Phillips, 2016).

Because of their high level of severity (for all road categories combined, 56% of fatal and serious injuries in Norway in the period 2013–2016 involved these two accident types), the current Norwegian National Action Plan for Road Traffic Safety has stated that their reduction is one of its main priority areas (NPRA, 2017). Therefore, it is essential to acquire knowledge about the risk factors that contribute to these accidents' occurrence and affect their consequences. One of the most critical factors affecting road safety is road infrastructure and environment (Elvik et al., 2009). More specifically, the configuration of the cross-section (i.e. lane and shoulder widths and the presence – or not – of a paved shoulder) is considered to be one of the major risk factors for head-on and single-vehicle accidents (Zegeer et al., 1994). Examples of other road-infrastructure risk factors are the road-surface conditions (Chen et al., 2017), presence of rumble strips (Khan et al., 2015), vertical and horizontal alignment (Zhang and Ivan, 2005), longitudinal marking (Park et al., 2012) or roadside conditions (Peng et al., 2012). The risk factors have variable impacts on road safety across accident severity levels and are characterised by their complex interactions (Chen et al., 2019).

The cross-sectional configuration influences the risk of accident occurrence because of its effects on drivers' behaviour. As reported in

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behavioural studies, lane and shoulder widths affect drivers' choice and variability with respect to lateral positioning and speed. The findings indicate that narrower lanes result in making the vehicle's lateral position less variable, speed reduction and overall position closer to the centre of the road (e.g. Evans and Charlton, 2006). Moreover, making shoulders wider contributes to vehicles traveling at higher speeds and maintaining lateral positions closer to the edge line (Mecheri et al., 2017). The findings from Dijksterhuis et al. (2011) suggest that the level of oncoming traffic is also an important factor for lateral positions. Furthermore, the lane and shoulder widths affect drivers' behaviour with regard to overtaking other vehicles (Mohaymany et al., 2015), their possibility for making recovery maneuvres (Lee et al., 2015) as well as their perception of the environment (Yang et al., 2014).

Since 1950, many accident-related studies have been conducted worldwide that have tried to estimate the magnitude of lane and shoulder widths' effects on levels of accident risk. From the early research conducted on this topic, the work of Zegeer et al. is frequently cited. For example, based on data collected from more than 25,000 km of rural two-lane roads in the US, Zegeer et al. (1980) calculated the accident rates for lane and shoulder width categories and their various combinations. They discovered that wide lanes and shoulders were associated with lower accident rates. In a later study, Zegger at al. (1994) analysed single-vehicle and head-on accident rates on rural low-volume, two-lane roads. They found that the related accident rates were lower on roads having lane widths > 3.0 m and wider shoulders compared to the same lane widths with narrower shoulders. In addition, for a given shoulder width, wider lanes were found to be associated with lower accident rates. These findings are generally consistent with human intuition: wider lanes and shoulders should be safer, as they provide more space for avoiding potential collisions. However, as Labi (2011) notes, lanes and shoulders that are too wide might actually have a negative safety effect because they might provide drivers with a false sense of safety, thereby contributing to reckless driving. This example of behavioural adaptation was illustrated by Gårder (2006), who analysed head-on accidents on rural two-lane collector and arterial roads in Maine (US). This study found a tendency showing that wider shoulders had a higher percentage of serious accidents. In turn, narrower roads might be characterised by safer driving behaviour; hence, they might contribute to a reduction in the number of accidents. This type of reduction was documented by Milton and Mannering (1998) for lanes narrower than 3.5 m. However, driving on excessively narrow lanes and shoulders might lower drivers' chance to manoeuvre and decrease the distance between oncoming vehicles (Labi et al., 2017). In addition, some studies, including one by El-Assaly and Hempsey (2000), reported no relationship between widths and safety on two-lane paved highways in Alberta (CAN). However, the authors emphasised that this result is not transferable to other regions, as all areas of the world have their own local characteristics that set them apart from others.

The most recent studies on safety effects of rural two-lane roads' width parameters confirm the variability in results; additionally, they use several different methodologies to do so. For instance, Gross and Donnell (2011) conducted a case-control study on a sample of roads in Pennsylvania (US). According to their results, lane widths between 3.0–3.35 m showed the highest level of risk, while 2.75 m and 3.5 m showed the lowest. Regarding shoulder width, their study documented that as width increased, risk levels decreased. Using a cross-sectional regression model, Gooch et al. (2016) quantified the safety effects of horizontal curves on rural two-lane roads in Pennsylvania (US). A combined width of two lanes measuring between 4.9 m–6.0 m was found to decrease accident frequency, while a width measuring between 6.0–7.0 m was found to increase it. As regarded combined shoulder width, values < 1.2 m were less safe than values between 1.2–3.6 m. Labi (2006) developed several crash prediction models (using the general negative binomial form) for 540 segments of rural two-lane roads in the US. While wider lanes were generally associated with lower accident rates, shoulder width was shown to have a significant negative influence on accidents' occurrence and severity levels. Lee et al. (2015) analysed roadway segments in Florida (US) (using a generalised nonlinear model) and found out that the accident rate was highest for a lane width of 3.65 m and lower for values less or greater than 3.65 m. In their study of 3594 two-lane road sections in Israel (using both case-control and negative binomial regression models), Gitelman et al. (2019) found that wider lanes (> 3.2 m) are associated with a higher risk for single-vehicle accidents. Regarding shoulder width, the study reports a non-monotonous link between the total shoulder width and accidents; more specifically, there is an increase in accident risk with an initial shoulder extension up to 2.2 m and a decrease in accidents with a further shoulder widening beyond this value.

The effects of lane and shoulder width might be considered in context of one another because of their potential interaction. For example, this interaction was considered in a study by Gross et al. (2009), who found that the optimal configuration with respect to safety appeared to be wider lanes and narrower shoulders. More recently, Labi et al. (2017) have developed a framework for determining the optimal allocation of shoulder and lane widths on different classes of two-lane rural roads.

Additionally, the accident-related data reported in the winter period have a different pattern compared to the non-winter periods. For example, the percentage of single accidents is typically higher, while the severity of accidents is less in snowy conditions. Tires' reduced grip as well as limited drivers' visibility and change of behaviour (such as reduced speed, less frequent overtaking, lower traffic volumes) in winter weather might explain this difference (Filtness and Papadimitriou, 2016). Zeng and Schrock (2013) demonstrated that treating the winter and non-winter data equally is likely to bias a shoulder's estimated safety effectiveness on the total number of accidents.

The diversity in the above findings, in particular with regard to shoulder widths, might be attributed to several factors, including 1) the different methodologies, models, and variables used by the authors, 2) the regional and national specifics regarding accident reporting and/or safety culture in general, 3) the quality and availability of data, 4) different sample sizes, and 5) different accident types analysed. The ideal method for estimating the effect of a geometrical parameter on accident risk would be to conduct an experimental study on an existing road network (Hauer, 2010). However, in the field of road safety research, conducting an experiment in a real traffic environment is largely unethical and uneconomical (Gross, 2013). Thus, when analysing the effects of lane and shoulder widths, statistical modelling is the most common method, using as it does existing accident databases and data about road geometry and traffic operation. As the effects of lane and shoulder widths on safety are not isolated, other road and traffic characteristics must be accounted for in the analysis. Due to this requirement, multivariable statistical models are typically used as they control for other road characteristics and traffic exposure (Gitelman et al., 2019). Many previous studies have applied an observational, cross-sectional approach, including Gårder (2006), who developed ordered probit models to look at the simultaneous influence of several variables on the accident severity. Similarly, Hosseinpour et al. (2014), calculated seven count-data models (e.g. standard negative binomial, random-effect negative binomial or zero-inflated negative binomial models) to study the effects of roadway characteristics on the frequency and severity of head-on accidents. However, according to Hauer (2010), the ability to use observational cross-sectional studies to draw cause–effect conclusions is controversial, mainly because there is concern that these models might contain an unknown number of confounding factors.

Therefore, before-after studies are generally preferred to cross-sectional studies (Hauer, 2010; Gross, 2013; Gitelman et al., 2019). The empirical Bayes approach is currently considered to be the state-of-the-art in these studies, as it accounts for regression-to-the-mean, changes in traffic volume, and other temporal factors that may change from a 'before' to an 'after' period. An example of this approach is a study published by Wu et al. (2015), who applied the methodology to evaluate how wider lanes and shoulders affect accident occurrence on 22 narrow pavement widening projects on rural two-lane roads in Texas (US). However, using the before-after approach to study the safety effects of lane and shoulder width is often challenging, as it requires a long period to collect enough data. Furthermore, a change of lane and/or shoulder width is usually accompanied by other geometrical/design adjustments, making it difficult to isolate the safety effect of a single variable due to other confounding factors.

Thus, given the limitations associated with both before-after and cross-sectional studies, an alternative method is needed. Hauer (2010) suggests that an observational epidemiological approach may present a viable alternative. The case-control method (CC method) is one such epidemiological approach that is suitable for analysing rare events (i.e. accidents). The most recent examples of CC method's application published in the road safety literature include US studies on 1) accident risk levels related to traffic oscillations in congestion (Zheng et al., 2010), and 2) different "policy-sensitive" factors on motorcycle accidents (Wali et al., 2018), 3) a South Korean study on the safety effects of highway terrain type on major rural roads (Choi et al., 2011), 4) a French study on the relationship between wearing a bicycle helmet and risking different types of injury (Amoros et al., 2012), 5) a spatial study that attempts to predict cycling accident risk in Brussels (Vandenbulcke et al., 2018), and 6) a UK study exploring the impact of traffic volumes and road characteristics on cycling injury risk (Aldred et al., 2018).

Only a few of the CC studies focused specifically on the safety effects of road design elements (Gross, 2013). Gross et al. published several articles and guides on the application of the CC method to evaluate the safety effects of road geometry, for example Gross (2013); Gross and Donnell (2011) and Gross and Jovanis (2007). Furthermore, the CC method was suggested as an alternative method for estimating safety effectiveness in A Guide to Developing Quality Crash Modification Factors (Gross et al., 2010), which was prepared for the Federal Highway Administration (US). The most recent examples of CC method applications include a study from Israel (Gitelman et al., 2019) and a US-China study that developed the accident modification factors of horizontal curve design features for single-motorcycle accidents (Xin et al., 2019).

Seen from road administrators' point of view, there is a practical need to optimise the design parameters of rural roads from the perspective of both safety and cost-benefit analysis; therefore, finding their optimal lane and shoulder widths is important. In Norway, the design parameters are provided in The Norwegian Road and Street Design Guideline (Håndbok N100, further referred to as the "N100 Guidelines"), which is published by the Norwegian Public Road Administration (NPRA) and revised periodically. Table 1 summarises the cross-sectional dimensions of the most common road categories from the last four editions of the N100 Guidelines. It is evident that while roads designed according to 2013 guidelines are the widest, the latest edition suggests narrower roads. Subsequently, it is apparent that lane and shoulder widths vary a lot within the existing road network depending on the year they were designed, constructed or reconstructed. Interestingly, according to Elvik (2017), there are no references to research and no scientific explanations in the N100 Guidelines regarding the changes of these design parameters.

The current N100 Guideline, published in May 2019, differentiates between three design categories relevant to rural two-lane undivided roads, having four possible combinations of lane and shoulder widths. These combinations are: 3.25 m + 1.0 m; 3.0 m + 0.75 m, 2.75 m + 0.5 m; and 1.5 m + 0.5 m. Along the cross-sections of these roadways, shoulders are typically paved. Signage is to be placed at least 0.5 m off the road shoulder, and lighting is generally not required. There is also a requirement for a safety zone extending from the lane edge beyond the shoulder when there are no roadside objects or non-recoverable slopes (or else there would be a need for guard rails); this depends on the factors of speed, AADT, and horizontal curvature. Lane widths are increased along low radius horizontal curves (R < 500 m). This widening is between 0.25 and 0.90 m, dependant on curve radius. Examples of rural two-lane undivided roads from Norway are shown on Fig. 1

2. Methodology

This study aims to estimate the safety effects of lane and shoulder widths on rural two-lane undivided road segments in Norway on total numbers of head-on and single-vehicle accidents, while also considering the differences between winter and non-winter accidents and their severity levels. The methodology of this study follows a matched CC approach for several reasons:

- To overcome the limitations of cross-sectional studies (i.e. control for confounding).
- It was practically impossible to apply a before-after study due to the lack of road sites where shoulder and lane widths were changed, with corresponding periods before and after the treatment.
- To test the application of the CC method in Norway.
- The results of the CC method in the form of odds ratios are very similar to accident modification factors, which was of interest to the NPRA.

The underlying conceptual basis for the CC method is the comparison of one group with another with respect to one or more characteristics of interest (Lilienfeld and Lilienfeld, 1979). The results of the CC method are presented in the form of odds ratios. The odds ratio is interpreted as the expected percentage increase or decrease of the outcome in question (i.e. the safety effect) due to the presence of the risk factor (a road parameter, e.g. lane width), compared to a baseline. In the case of a categorical variable, the baseline is a variable's reference category.

The crucial step in a CC study is defining the cases and control (Gross, 2013). Ambiguous or broad definitions may lead to misclassification and will likely produce unclear results. Cases and controls should be representative of the sites of interest - in other words, the chance of being included in the study must not be associated with the studied risk factor (Gross et al., 2010). In CC studies related to road geometry, cases and controls are typically selected from a group of road segments. Cases are understood to be road segments with at least one related accident, while controls are represented by segments without any accident within the selected study period. Two basic types of CC studies exist; these are distinguished by the method used to select the controls. The first is a non-matched CC study in which controls are

Table 1
Changes of basic cross-sectional parameters of two-lane rural roads in Norway (based on Elvik, 2017).

N100 edition	1981		1992		2013		2019	
AADT	1,500-4,000	4,000-8,000	1,500-5,000	5,000-10,000	< 4,000	4,000-6,000	< 4,000	< 6000
Lane width (m)	3.00	3.25	3.00	3.25	3.25	3.50	3.00	3.25
Shoulder width (m)	0.50	1.00	0.75	1.00	1.00	1.00	0.75	1.00
Total width (m)	7.00	8.50	7.50	8.50	8.50	10.00	7.50	9.00

Fig. 1. Examples of two-lane rural undivided roads from Norway (photo by P. Pokorny).

included without regard to the cases' number or characteristics. The second type is a matched CC study where controls are registered based upon some characteristic(s) of the case. There are two main types of matched design: 1) one-to-one matching (i.e. one case to one control, or one case to a specific number of controls) and 2) frequency-matching where matching is based upon the distributions of the characteristics among the cases. The maximum matching ratio is recommended to be 1:4, as a larger ratio does not increase the power of the study (Woodward, 2013).

The idea of matching is to match on potential confounding risk factor(s) in order to remove the confounding effect(s). Confounders include those variables that either completely or partially account for the apparent association between an outcome and a risk factor. For example, consider the effect of lane width on accident risk levels. One potential confounding variable is AADT, as it is both a significant predictor of accident risk levels and is associated with lane width (higher-class wider roads are usually associated with relatively high AADT). Mansournia et al. (2018) pointed out that matching strong confounders (like age and gender in medical studies) should be a core design option, while matching variables unrelated to the outcome should be avoided. Schlesselman (1982, cited in Xin et al., 2019) noted that if matching includes more than one variable, these matching variables should not be strongly correlated with each other. The other variables and weak confounders that affect the study's outcome might be better addressed via subsequent model-based adjustments as covariates. The identification of correct confounders and covariates is therefore crucial in matched CC studies.

Processes conducted within the CC method applied in this study may be described in the following three steps: (1) segmentation, (2) identification of related accidents, and (3) matching and statistical analysis.

2.1. Segmentation

In order to identify cases and controls, a road network of interest needs to be specified and divided into the segments using constant geometric and operational characteristics. In this study, the Norwegian National Road Databank NVDB provided geometric and operational data on the existing road network. An initial segmentation (a road network with speed limits and numbers of lanes) was done using proprietary in-house database tools. The majority of GIS processing (segmenting with other road attributes, finding intersections and urban areas, filtering, data management) was managed in Feature Manipulation Engine, a visual workflow editor (FME Software, 2020). The final data processing, visualisation and quality control were done in a desktop geographical information system (QGIS Development Team, 2020). The segmentation procedure was carried out as a step-by-step process comprising the following steps: (1) selecting the network of interest, (2) initial segmentation, (3) merging the adjacent segments with similar characteristics and (4) creating the final dataset by eliminating the segments with uncommon attribute values. Throughout this process, a visual and statistical control of the data (e.g. checking the segments' minimum and maximum lengths) was carried out in order to identify potential issues, anomalies, or obvious mistakes.

The selection of the road network of interest followed these principles:

- *Road category*: European, Regional and District roads in Norway (so called ERF roads)
- *Cross-sectional configuration*: Two-lane roads without physical median separation
- *Environment*: Rural roads, defined as the roads outside of urban areas. An urban area is defined as a registered settlement with at least 200 inhabitants and with the distance between houses not exceeding 50 m (SSB - Statistics Norway (Statistisk sentralbyrå), 2020). This definition created broken polygons around the urban areas, which typically contained many "bays" (see Fig. 2, yellow area). The road sections that are located in these bays would be considered rural according to the definition; however, many of them carry some urban characteristics (e.g. mixed traffic, sidewalks, zebra crossings or lighting). Therefore, a convex hull (i.e. the smallest bounding convex polygon around points, lines, or polygon features) was created around each urban area to cover the bays (see Fig. 2, orange area). In the end, only the roads outside these convex hulls were considered to be rural and so were selected for analysis.
- *Specific layouts*: This study is concerned with ERF road sections of standard road configurations. Intersections were not included in the analysis. In order to eliminate possible bias due to the influence of intersection geometry and traffic patterns on the safety of adjacent road sections, a buffer with a radius of 100 m was created around the intersections, and the sections inside the buffers were excluded from the analysis. Note, that intersections between ERF roads and roads with low functional classes (including forest, agriculture, gravel, farm access roads) were not considered to be intersections. Furthermore, tunnels of any length and bridges (over 20 m in length) were excluded from the analysed road network because of their safety specifics (Elvik et al., 2019; Caliendi et al., 2013).
- *Speed limits*: Sections with low speed limits ($\leq$50km/h) were excluded from the road network of interest. Based on visual inspection, these sections were either typically situated in small urban settlements (that were not included in the applied definition of urban area) or part of a specific location, such as rest areas. Furthermore, segments with high speed limits ($\geq$90km/h) were excluded as well, as these are not typical for two-lane roads.

During the initial segmentation step, a change of selected attributes created a segment. These attributes were: the speed limit, county, horizontal alignment (straight or curved – as straight being considered sections having $R = 0$ or $R > 1750$ m), shoulder and lane width, AADT, share of long (over 5,6 m) vehicles in AADT. This process created an enormous number of very short segments; consequently, the adjacent segments with similar values with respect to speed limit, horizontal alignment in addition shoulder and lane width in the 0.5 m range were merged. This led to the creation of 325,044 segments with a total length of 36,873 km. In the next step, only the segments matching the following criteria were included in the final dataset:

- Known values of all attributes

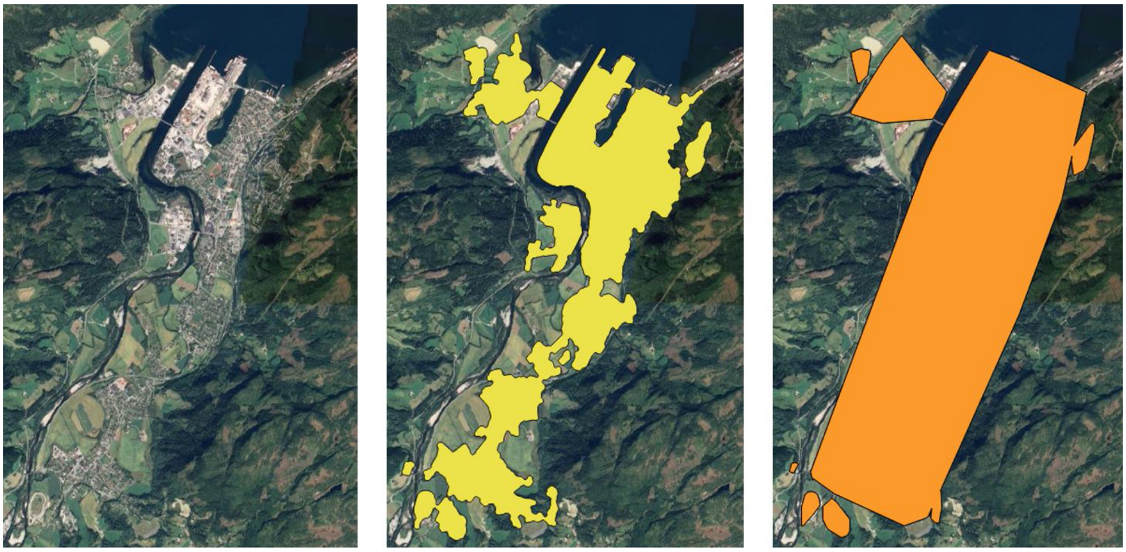

Fig. 2. Definitions of urban area: satellite image of a city (left); urban area according the "official" definition (yellow area, middle); urban area defined with convex hulls around the urban area (orange, right) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

- Common values of all attributes (the following attribute values are considered uncommon: AADT $<$ 50 veh./day; share of long vehicles from AADT $>$ 50%; traffic lane width $>$3.75 m and $<$1.50 m; shoulder width $>$2.00 m)
- Length of the segments between 100 – 500 m (segments $>$500 m were eliminated because they are rare in the dataset /n = 5788/, while segments $<$100 m /n = 201,335/ were eliminated, as it is often the case that an accident cannot be solely attributed to the short segment because of the inaccuracies that occur when an accident location is reported)

This elimination resulted in the final dataset of 71,999 segments with a total length of 14,050 km. Each segment contains the following attributes: a list of all curved radii ($R_{i)}$ and curve lengths (L_i), values of shoulder width (S_w) and lane width (L_w), speed limit, county, AADT, share of long vehicles from AADT and the total length. The weighted averages for radius (R_w), shoulder and lane widths were calculated for each segment. Because of the segmentation's criteria, the values of these attributes are not diverse along the segments; therefore, the average values may represent these characteristics. The attributes were further classified into categories (see Table 2). For horizontal alignment, the direction of radii and an average value of radius R = 200 m were set as the boundary for distinguishing the categories (Elvik, 2013). Regarding region, a traditional division of the country was applied, and 11 counties were merged into five regions. Categories for lane and shoulder widths and AADT are based on the values from the N100 Guidelines.

2.2. Identification of related accidents

In Norway, accidents involving at least one vehicle that have taken place on public or private roads, streets or places open to general traffic are regularly recorded in all jurisdictions. Data is electronically submitted by the police to the Norwegian Public Roads Administration and The Central Bureau of Statistics, where it is revised, verified and stored within The National Database of Road Data NVDB. Each record contains GPS coordinates of the accident location. Since 1964, only accidents involving personal injuries have been included in the statistics; however, in some cases accidents without injury are reported as well (e.g. accidents with massive property damage). The degree of injury is broken down into four categories: fatal (within 30 days), critically injured (i.e. life-threatening or permanent injuries), seriously injured (i.e. major, but not life-threatening injuries) and slightly injured (i.e. minor fractures or scratches, when hospitalisation is not required).

In this study, the related accidents are considered head-on and single-vehicle run-off-the-road accidents involving motorised vehicles (excluding two-wheeled-vehicles) that were recorded in NVDB in the period 2013 – 2017. The accident data were assigned to the selected road network based on their GPS.

For the purpose of obtaining a more detailed analysis, the related accidents were further categorised as non-winter, winter, slight and severe. Non-winter accidents are those recorded from April to October that occurred on ice-free/snow-free roads. Winter accidents are considered accidents recorded from November to March in addition to those on ice/snow slippery surfaces recorded in non-winter months. Severe accidents were considered to be those causing fatal, critical and

Table 2
Attributes and their categories.

Attributes	Lane width (m)[a]	Shoulder width (m)	Speed limit (km/h)	Region	AADT (veh/day)	% of long veh. from AADT	Horizontal alignment
Categories	1.50–1.75	0.00–0.25	60	North	$<$500	0–8	Straight
	1.76–2.00	0.26–0.50	70	South	501–1,500	8–12	Single curve (R $>$ 200 m)
	2.01–2.25	0.51–0.75	80	Middle	1501–4000	$>$12	Single curve (R $<$ 200 m)
	2.26–2.50	0.76–1.00		East	4,001–6,000		Curves - same dir. ($R_w > 200$ m)
	2.51–2.75	over 1.00		West	6,001–8,000		Curves - same dir. ($R_w < 200$ m)
	2.76–3.00				$>$8000		Curves - diff. dir. ($R_w > 200$ m)
	3.01–3.25						Curves - diff. dir. ($R_w < 200$ m)
	3.26–3.50						
	3.51–3.75						

[a] Including any widening occurring at horizontal curves.

severe injuries, while others were considered to be slight accidents.

2.3. Matching and statistical analysis

In matched case-control studies, conditional logistic regression is applied to estimate the odd ratios (i.e. whether the exposure to a risk factor is disproportionately distributed between cases and controls). In this study, conditional logistic regression has been calculated in SPSS using the COXREG procedure. The conditional partial likelihood maximized by the COXREG procedure is the same one that results from conditional logistic regression. The first step of this statistical analysis included defining the cases and controls. All five years were analysed together because of the relatively small number of related accidents and their stable annual numbers. The case was defined as a segment that experienced at least one related accident during the entire study period. If there were more accidents recorded on one segment during the study period, this segment was considered to be several individual cases (number of accidents = number of cases). This type of approach causes the potential effects of these multiple accident segments' characteristics, as documented in Gross (2013), to become more significant. Categorical variable AADT was selected as the only matching variable, as it is associated with both road width and related accidents. Another classical confounding variable, speed, was used as one of the independent variables in the model rather than a matching variable because, according to the descriptive analysis, the posted speed limit did not appear to have any significant associations with road width.

Categorical four-to-one matching has been applied (i.e. first categorising the matching variable and then finding four controls from the same combined set of matching categories for each case). The matched set is called *strata*. The selection of controls for matching was separately carried out in Excel for each AADT category using the RAND function (a generator of random unique numbers).

Five models were calculated:

- Model #1 for all related accidents
- Models #2 and #3 for different severity levels of related accidents
- Models #4 and #5 for different seasons

The models determine the odds ratios for lane and shoulder width categories while controlling for the effects of AADT and adjusting for the effects of region, speed limit, segment length, share of long vehicles in AADT and horizontal alignment. The odds ratios Exp (B), are interpreted as the expected percent increase or decrease of the outcome in question (i.e. presence of a related accident) due to the occurrence of the risk factor (shoulder and lane width categories). In all models, the dependent variable was the binary variable status of the segment (with values “case” or “control”). The independent variables in all the models were the segments' categorised attributes and continuous length (see Table 2). The most frequent categories for each attribute were selected as the reference categories (see Table 4).

3. Results

3.1. Segmentation

The descriptive characteristics of the attributes and their categories in the final dataset (n = 71,999 segments) are shown in Tables 3 and 4.

The most common (pertaining to the segments' total length and number of kilometres driven on them) combinations of shoulder and lane widths in the sample are those with lane widths between 2.50–3.25 m and shoulder widths up to 0.50 m. Combinations with shoulders over 1.00 m are rare. The shoulder width 0.00 – 0.25 m and lane width 2.76 – 3.00 m were selected as the reference categories. Table 4 summarises the distribution of categories related to other segments' attributes. The most frequent categories are straight horizontal alignment, 80 km/h speed limit, AADT between 0–1,500 veh./day and share of long vehicles between 8–12% from AADT. The region with the highest number of segments is eastern Norway, which is the second largest and most populated region in Norway (50.4% of the entire Norwegian population lives in this area).

3.2. Related accidents

The final dataset consists of 1886 head-on and single-vehicle accidents. According their consequences, 97 were fatal, 37 critical, 228 serious, 1318 slight and 206 no-injury accidents. The annual number of accidents over the five-year period was stable, with an annual average of 377 (min. = 338, max. = 416, and standard deviation st.d. = 25.4). The numbers of accidents broken down according to the season (winter/ non-winter), type (single/ head-on) and severity (fatal/critical + serious/slight/no injury) are shown in Table 5.

In general, the sample showed that there were less accidents recorded in the winter (n = 861) than in the non-winter period (n = 1025), and there were almost three times more single-vehicle accidents than head-on accidents (1387 vs. 500). According to the chi-square test, there is a significant difference (95% significance level, p-value < 0.00001) between the shares of single-vehicle/head-on accidents in the winter and non-winter periods (the share of head-on accidents is higher in winter). The consequences differ significantly between the accident types, with head-on accidents having a higher share of severe and fatal accidents, (95% significance level, p-value < 0.00001). This also occurs between the seasons, with non-winter accidents having a higher share of fatal and severe accidents (p-value = 0.023188). Looking at the distribution of severity levels across the lane and shoulder width categories, the wider lanes (over 2.50 m) had a significantly higher share of severe accidents than narrower lanes (p-value = 0.025298), while there was no difference regarding shoulder width.

3.3. Statistical analysis

As described in the methodology, five models were calculated. The final dataset contains 70,219 segments without any accidents (controls), while 1780 segments experienced at least one accident (cases). Segments containing more than one accident are very rare (n = 93, with max. 4 accidents on a segment). As segments with multiple accidents were treated as multiple same segments (e.g. a segment with three accidents was considered as three same segments), the number of cases was 1,886. In models #2 - #5 (for specific accident types), the segments with other types of accidents were not considered as controls; consequently, these were omitted from analyses. Table 6 shows the number of cases and controls for each model and for each matching category of AADT.

As a result of the matching, the matched sets (strata) were created for each model. Each stratum contains five segments comprised of one case and four matched controls. Model #1 (all accidents) involves 9430 segments in 1886 matched sets; model #2 (severe accidents) involves 1,650 segments in 330 matched sets; model #3 (slight accidents) involves 7,445 segments in 1,489 matched sets, model #4 (winter accidents) involves 4,080 segments in 816 matched sets, and model #5 (non-winter) involves 4,875 segments in 979 matched sets. The results of the models, including the parameter estimates (B), odds ratios (Exp*B*), 95% confidence intervals (95%CI) for odds ratios and significance (Sig.), are presented in the sections below. Model #1 for all accidents is presented in more detail and involves all independent variables, while, only shoulder and lane widths are presented for models #2 - #5.

3.3.1. Model #1 (All accidents)

Regarding shoulder widths, the model results (see Table 7) indicate the highest risk for the 0.00-0.25 m and 0.76-1.00 m shoulder categories, while the lowest risk for 0.51-0.75 m category. For lane widths,

Table 3
Percentage shares of length and vehicle-km driven for combinations of lane and shoulder width categories.

		Shoulder width categories (m)											
		0.00–0.25		0.26–0.50		0.51–0.75		0.76–1.00		1.01–2.00			
		length	veh_km	length	veh_km	length	veh_km	length	veh_km	length	veh_km	total length	total veh_km
Lane width categories (m)	1.50 – 1.75	1.88%	0.42%	1.44%	0.23%	0.66%	0.09%	0.37%	0.05%	0.35%	0.04%	4.70%	0.83%
	1.76 – 2.00	2.59%	0.64%	2.21%	0.42%	0.80%	0.13%	0.42%	0.06%	0.34%	0.04%	6.36%	1.29%
	2.01 – 2.25	3.77%	1.19%	2.92%	0.65%	1.50%	0.30%	0.51%	0.10%	0.24%	0.04%	8.94%	2.28%
	2.26 – 2.50	6.06%	2.50%	3.70%	1.28%	1.68%	0.46%	0.36%	0.09%	0.15%	0.04%	11.95%	4.37%
	2.51 – 2.75	8.03%	4.72%	5.73%	3.16%	2.39%	1.08%	0.52%	0.21%	0.20%	0.07%	16.87%	9.24%
	2.76 – 3.00	10.92%	11.42%	9.26%	9.78%	4.15%	4.10%	1.04%	1.01%	0.45%	0.45%	25.82%	26.76%
	3.01 – 3.25	7.25%	12.31%	6.16%	11.18%	2.48%	4.41%	0.65%	1.14%	0.24%	0.47%	16.78%	29.51%
	3.26 – 3.50	2.86%	7.09%	2.22%	6.13%	1.08%	3.14%	0.24%	0.65%	0.14%	0.42%	6.54%	17.43%
	3.51–3.75	1.00%	3.76%	0.69%	3.06%	0.25%	1.00%	0.06%	0.28%	0.04%	0.20%	2.04%	8.30%
total		44.36%	44.05%	34.34%	35.89%	14.98%	14.72%	4.17%	3.59%	2.15%	1.75%	100.00%	100.00%

Table 4
Numbers of segments and shares of their length with respect to other attributes and their categories.

Attribute	Category	nr. of segments	length (%)
Speed limit (km/h)	60	10,727	14.90%
	70	3317	4.61%
	80 *(reference)*	57,955	80.49%
Horizontal alignment	curves - diff. dir. ($R_w > 200$ m)	17,816	29.35%
	curves - diff. dir. ($R_w < 200$ m)	4913	6.68%
	curves - same dir. ($R_w > 200$ m)	6976	9.12%
	curves - same dir. ($R_w < 200$ m)	1018	1.04%
	single curve ($R > 200$ m)	5455	5.67%
	single curve ($R < 200$ m)	369	0.33%
	straight *(reference)*	35,452	47.80%
AADT (veh./day)	< 500	31,843	44.69%
	501 – 1,500	21,956	30.23%
	1,501 – 4,000	13,515	18.67%
	4,001 – 6,000	2578	3.52%
	6,001 – 8,000	870	1.20%
	> 8000	1237	1.69%
Share of long vehicles	low	14,388	19.59%
	normal*(reference)*	36,615	50.73%
	high	20,996	29.68%
Region	East *(reference)*	26,966	37.08%
	Middle	9450	12.89%
	North	17,021	24.55%
	South	4997	6.90%
	West	13,565	18.58%

the results indicate an increased risk with increasing lane width up to 3.25 m, after which the risk steeply drops. When considering other variables, horizontal alignment particularly had significant effects on related accidents, with higher curvature (curves with radii < 200 m) showing the highest levels of risk.

3.3.2. Model #2 – 5 (Severe/Slight accidents and Winter/Non-winter accidents)

Regarding shoulder widths, the results of models # 2 - 5 (see Table 8) indicate decreasing trends for all odds ratios up to 0.26-0.50 m category. For shoulder wider than 0.50 m, the odds ratios show more diversity. The odds ratio for severe accidents decreases further, while slight accidents show an opposite trend. Furthermore, the odds ratio for winter accidents increases (particularly for the 0.76-1.00 m category), while stay stable for non-winter accidents.

For lane widths up to 3.25 m, the odds ratios from all models show an increasing trend with increasing widths (with exceptions at 2.26-2.50 m category for non-winter and severe accidents). The highest odds ratios values for the narrowest lane widths (up to 2.25 m) have non-winter accidents. From 3.25 m, the odds ratios show much more diversity – for example, they increase for winter accidents, while are decreasing for non-winter accidents. Furthermore, the odds ratio for severe accidents are higher than for slight accidents for category 3.26-3.50 m. However, only a few results of models #2 - #5 are significant.

4. Discussion - results

4.1. Related accidents

There were fewer related accidents recorded in winter, which might be explained by less traffic and a learning effect that occurs when people often drive in unfavourable environmental and surface conditions. Drivers are used to drive on snow- or ice-covered roads in Norway and, as shown by Niska (2006), driving more under these conditions is associated with reduced accident rates. The share of head-on accidents from all related accidents was significantly higher under winter conditions, while the number of single-vehicle accidents was lower in winter compared to non-winter. This finding does not correspond with studies from other countries (Filtness and Papadimitriou, 2016). Lower numbers of single-vehicle accidents might be explained by the learning effect mentioned above, while narrower roads or limited space for escape manoeuvres due to the presence of snow might affect the higher number of occurrences of head-on accidents in winter. There were also

Table 5
Numbers and types of related accidents.

	Winter			Non-winter			Total	
	Single-vehicle	Head-on	Total	Single-vehicle	Head-on	Total	Single-vehicle	Head-on
Fatal	12	25	37	33	27	60	45	52
Critical + Serious	47	55	102	103	60	163	150	115
Slight	439	186	625	578	115	693	1017	301
No injury	81	16	97	93	16	109	174	32
Total	579	282	861	807	218	1025	1386	500

Table 6
Numbers of cases and controls for the models for each matching category of AADT

AADT	CASES					AVAILABLE CONTROLS
	Model#1 – all accidents	Model#2 - severe	Model#3 - slight	Model#4 - winter	Model#5 - non-winter	
< 500	189	35	154	78	111	31,654
501 – 1500	577	101	455	254	299	21,408
1501 – 4000	730	116	588	324	359	12,834
4001 – 6000	189	31	148	86	95	2401
6001 – 8000	63	11	49	25	33	812
> 8000	138	36	95	49	82	1110
Total	1886	330	1,489	816	979	70,219

significant differences in accident consequences according to accident type and season. The severity of head-on accidents was higher than single accidents, which may be explained by the accident dynamics typical for head-on accidents, when two cars traveling in opposite directions collide with each other. In addition, similar to many other studies (Filtness and Papadimitriou, 2016), the accidents recorded under non-winter conditions were more severe compared to winter accidents, which might be explained by higher speeds under non-winter conditions.

4.2. Risk factors

As described in the introduction, the findings of studies on the accident risk related to lane and shoulder widths are diverse. These differences are caused, among others, by the covariates and methods that are used (Filtness and Papadimitriou, 2016). The result of this study contributes to this diversity of findings. When interpreting the results, it is necessary to consider that the two-lane rural roads in Norway have typically constrained design compared to other countries; for example, it is very rare to find shoulders over 1.00 m wide in Norway. The odds ratios delivered from all models are graphically compared in Fig. 3, both for shoulder width (left figure) and lane width (right figure).

Model #1, which was calculated for all related accidents, provided more significant results, particularly for lane widths, than did any other models. Regarding shoulder width, the model indicates a non-monotonous link between risk and width categories. The highest level of risk was found for the narrowest shoulder category 0.00 – 0.25 m. The level of risk then decreases to the minimal value for the category 0.51-0.75m. Yet as shoulder width increases to 0.76-1.00m, the risk increases once again, followed by another decrease for the widest category. This finding supports the results from other studies, that the presence of too narrow(er) shoulders increases the risk of accidents on two-lane rural roads (Filtness and Papadimitriou, 2016). It might be that very narrow/non-existing shoulders do not provide enough opportunities for potential evasive manoeuvres. Conversely, wider shoulders ((0.76-1.00 m in the Norwegian context) might contribute to higher speeds, and

Table 7
Results of model #1.

Independent variable	*Categories*	B	SE	Wald	Sig.	Exp (B) – Odds ratio	95,0% CI	
							lower	Upper
Shoulder width (m)	*0.00-0.25*			6.792	0.147	1.000	1.000	1.000
	0.26-.050	−0.061	0.063	0.961	0.327	0.940	0.832	1.063
	0.51-0.75	−0.224	0.088	6.399	0.011	0.800	0.672	0.951
	0.76-1.00	−0.020	0.157	0.016	0.900	0.981	0.721	1.334
	over 1	−0.180	0.230	0.614	0.433	0.835	0.532	1.311
Lane width (m)	*1.50-.75*	−1.145	0.353	10.501	0.001	0.318	0.159	0.636
	1.76-2.00	−0.811	0.250	10.523	0.001	0.444	0.272	0.725
	2.01-2.25	−0.490	0.185	7.017	0.008	0.613	0.426	0.880
	2.26-2.50	−0.273	0.137	3.993	0.046	0.761	0.582	0.995
	2.51-2.75	−0.181	0.096	3.550	0.060	0.835	0.692	1.007
	2.76-3.00			87.819	0.000	1.000	1.000	1.000
	3.01-3.25	0.114	0.073	2.432	0.119	1.121	0.971	1.293
	3.26-3.50	−0.497	0.096	26.919	0.000	0.608	0.504	0.734
	3.51-3.75	−0.772	0.156	24.473	0.000	0.462	0.340	0.627
Horizontal alignment	*Straight*			160.467	0.000	1.000	1.000	1.000
	Curves_diff. dir., R > 200	0.579	0.066	76.060	0.000	1.785	1.567	2.033
	Curves_ diff. dir., R < 200	0.890	0.117	57.702	0.000	2.435	1.935	3.063
	Curves_same dir., R > 200	0.518	0.086	36.664	0.000	1.679	1.420	1.986
	Curves_same dir., R < 200	1.453	0.188	59.466	0.000	4.277	2.956	6.187
	Single curve R > 200	0.138	0.108	1.623	0.203	1.148	0.928	1.419
	Single curve R < 200	1.128	0.348	10.502	0.001	3.090	1.562	6.115
Share of long vehicles	*Low (< 8%)*	0.037	0.077	0.234	0.629	1.038	0.893	1.206
	Normal (8-12%)			0.248	0.883	1.000	1.000	1.000
	High (> 12%)	0.017	0.063	0.070	0.791	1.017	0.898	1.152
Region	*East*			18.191	0.000	1.000	1.000	1.000
	Middle	−0.062	0.104	0.356	0.551	0.940	0.766	1.153
	North	−0.241	0.084	8.165	0.004	0.786	0.666	0.927
	South	0.077	0.104	0.541	0.462	1.080	0.880	1.324
	West	0.156	0.073	4.588	0.032	1.168	1.013	1.347
Speed limit (km/h)	*80*			10.701	0.005	1.000	1.000	1.000
	70	0.153	0.094	2.656	0.103	1.166	0.969	1.402
	60	−0.205	0.082	6.326	0.012	0.814	0.694	0.956
Length	*continuous*	0.004	0.000	234.616	0.000	1.004	1.004	1.005

Table 8
Results of models #2-#5.

Independent variable	Categories	SEVERE		SLIGHT		WINTER		NON-WINTER	
		Odds ratio	Sig.	Odds ratio	Sig.	Odds ratio	Sig.	Odds ratio	Sig.
Shoulder width (m)	0.00-0.25	1	0.937	1	0.151	1	0.757	1	0.533
	0.26-.050	0.996	0.978	0.943	0.395	0.919	0.377	0.953	0.574
	0.51-0.75	0.965	0.869	0.795	0.02	0.881	0.349	0.827	0.125
	0.76-1.00	0.852	0.643	0.767	0.133	1.128	0.601	0.822	0.373
	over 1	0.664	0.435	0.919	0.742	0.901	0.773	0.778	0.405
Lane width (m)	1.50-1.75	0.117	0.043	0.266	0	0.154	0.001	0.266	0.004
	1.76-2.00	0.28	0.051	0.422	0.001	0.244	0.002	0.623	0.132
	2.01-2.25	0.54	0.166	0.59	0.009	0.445	0.006	0.816	0.397
	2.26-2.50	0.401	0.02	0.682	0.009	0.677	0.055	0.72	0.073
	2.51-2.75	0.911	0.688	0.822	0.065	0.883	0.396	0.842	0.188
	2.76-3.00	1	0.074	1	0.001	1	0	1	0.028
	3.01-3.25	1.033	0.852	0.99	0.895	1.046	0.685	1.041	0.685
	3.26-3.50	1.254	0.299	0.92	0.426	1.06	0.675	0.881	0.333
	3.51-3.75	0.844	0.61	0.915	0.569	1.496	0.053	0.698	0.064

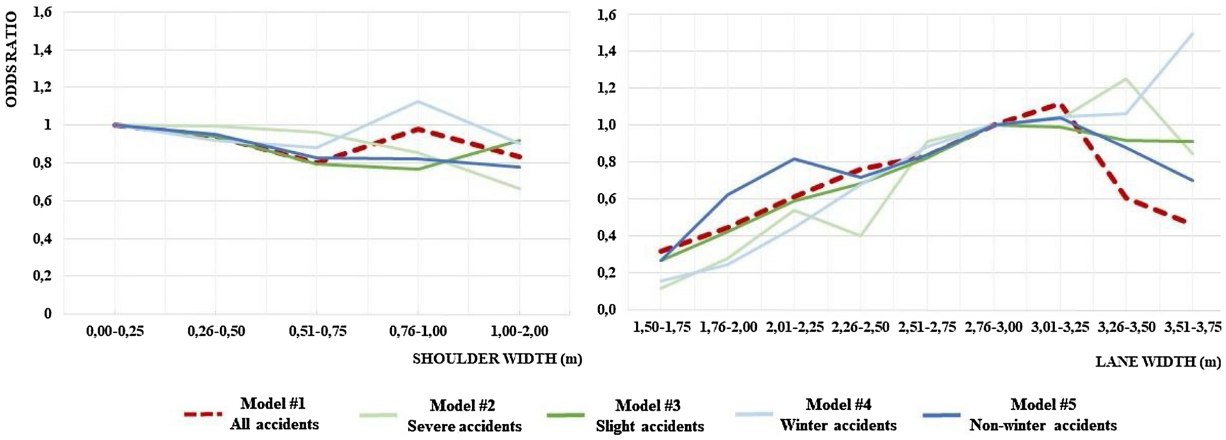

Fig. 3. Graphic illustration of the odds ratios for shoulder (left) and lane (right) widths for all models.

thereby higher levels of risk (Gitelman et al., 2016). However, this is not relevant for the widest shoulder category, which has lower risk. This might be explained that then is enough space for evasive or recovery manoeuvres.

For lane width, the model indicates the lowest risk being associated with lanes between 1.50-2.00 m. There is an increasing trend of odds ratios with increasing widths up to 3.25 m. For the wider lanes, the risk drops. While this finding is not fully consistent with a large group of studies that report increased safety levels for wider roads (such as Zegeer et al., 1994 or Wu et al., 2015), this type of result might be explained by lower speeds on narrow roads (Milton and Mannering, 1998; Chen et al., 2017). Conversely, drivers choose to drive at higher speeds on wider roads because they have a false sense of security (Labi, 2011). The low risk on the widest roads might be attributed to higher standards of these roads from a safety perspective.

Models #2 - #5 indicate that there are differences in risk levels for the same lane/shoulder width categories with respect to the season (winter/non-winter) and severity levels (severe/slight) of the related accidents. However, only a few odds ratios were significant, which is likely associated with the low number of cases. Nevertheless, together with the findings from descriptive statistics on related accidents, the consideration of season and severity differences should be included in accident models.

Considering the other variables, the horizontal alignment had significant effects on related accidents. Specifically, the single and multiple one-direction curves with R < 200 m showed the highest risk. This finding is in accordance with many studies, as summarised by Filtness and Papadimitriou (2016).

5. Discussion - methodology

Several points deserve consideration when discussing the applied methodology. An adjustment for exposure to risk was made through matching on AADT only. Speed, which is another traditional matching variable, was not used for matching but was included in the model as a covariate. Only the speed limit was available as a surrogate measure for speed in this study; descriptive statistics did not indicate that it was a strong confounding factor for this specific sample. In addition to the covariables used in the model, it could be beneficial to add several other variables as well, including the vertical alignment, specific combinations of horizontal elements (e.g. single curve after long tangent), roadside conditions, type of shoulder (paved/gravel) or existence of rumble strips. However, a higher number of variables would increase the number of segments (and make them much shorter), which would in turn make the analysis more complicated. Another aspect of the analysis to note is the potential bias toward the results due to the removal of segments with unknown shoulder widths. Most of these segments are on low-volume narrow roads, and this could be a confounding factor. Furthermore, the quality of data might not be consistent throughout the regions. For example, there were more segments with missing data on the share of long vehicles in region Middle (Trøndelag) than in other regions. In order to account for these inconsistencies, the independent variable region was used in the models.

One specific Norwegian consideration in modelling safety is the high safety level - Norway has one of the lowest road accident risks in the world (Adminaite-Fodor et al., 2019). This means that the available numbers of related accidents are low; therefore, the numbers of cases for some categories of AADT/shoulder/lane width are very limited. In order to deal with that, this study applies five years' analysis period. Such period is long enough to provide a sufficient number of cases for the most frequent shoulder and lane width categories, while short enough to ensure that the road-geometry and traffic conditions remained relatively constant on majority of the segments. Obviously, the conditions have changed on some segments during this time period which adds bias into the results.

This study does not consider motorcycle accidents. As motorcyclists comprise a road user group with high injury risk on rural roads, a follow-up study looking more closely at this group is recommended.

The strength of this study lies in its large dataset and data quality, as using GIS tools allows the creation of more precise and efficient segmentation. Furthermore, it was possible to define rural areas more precisely using the concept of a convex hull in the segmentation process. When interpreting the results, it is important to consider the sample's specifics. Most segments in this study have a constrained design (with narrow lanes up to 3.00 m and shoulders up to 0.50 m), 80 km/h speed limit and low AADT (up to 1,500veh/day). Furthermore, country-specific factors must be considered, particularly Norway's well-developed safety culture as well as its significant regional climate and geographical differences.

6. Conclusion

This study estimated the safety effects of lane and shoulder widths on head-on and single-vehicle accidents on rural two-lane undivided roads in Norway while accounting for impacts of other road and traffic characteristics. The study used a sample of 71,999 roadway segments and 1886 related accidents. A matched case-control method was applied to calculate the odds ratios for lane and shoulder width categories. An adjustment for exposure to risk was made through matching on AADT with a matching ratio of 1:4 cases to controls. The results suggest that it is relevant to consider winter and non-winter accidents as well as severe and slight separately when studying the effects of lane and shoulder widths on the occurrence of head-on and single-vehicle accidents. However, this consideration requires a sufficient number of cases (i.e. accidents). When examining lane and shoulder widths for all related accidents, the lane widths 1.50–2.50 m and shoulder widths $0.50 - 0.75$ m were relatively safer than other categories on Norwegian two-lane rural undivided roads. Such results contribute to further knowledge about safety within design of road cross-sections and can be used by road authorities when determining design standards, particularly on narrower rural roads.

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CRediT authorship contribution statement

Petr Pokorny: Formal analysis, Methodology, Writing - original draft. **Jan K. Jensen:** Data curation. **Frank Gross:** Writing - review & editing. **Kelly Pitera:** Supervision, Writing - review & editing, Project administration.

Declaration of Competing Interest

None.

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