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Speed responses of trucks to light and weather conditions

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Abstract: Light conditions are essential factors in traffic safety, but the relationship between light conditions and vehicle speed is not fully understood and has rarely been examined for trucks. We asked the following questions: I) if vehicle speed between brighter and darker conditions in clear weather will be different? II) if vehicle speeds are lower during rain and snow than in clear weather conditions? and if so III) if the speed reduction in rainy and snowy weather conditions is more substantial on roads without road lighting in darkness? We investigated how the speed of trucks was affected by weather conditions (clear, rain, and snowfall), daylight, darkness, and road lighting by using traffic and weather data from 25 locations on the Swedish road network. Seventeen of the 25 locations were roads with road lighting. Speed responses by 5,344,287 vehicle passages by trucks was included in the analyses, more specifically 3,659,940 passages by light-duty vehicles and 1,684,347 passages by heavy-duty vehicles. The data was extracted from hourly measurements for the period 2012-09-01 to 2014-05-31. No evidence of consistent patterns of speed differences with respect to lighting conditions (darkness, daylight, twilight or road lighting) under clear weather conditions were detected. Truck speeds decreased in response to snowfall, but not to rain, with the decrease dependant on the amount of snow. Effects of road lighting on speed reduction in rainy and snowy weather was not shown.

Subjects: Transport & Vehicle Engineering; Sustainable Transport Engineering; Civil, Environmental and Geotechnical Engineering; Transportation Engineering; Transport Planning

Keywords: LDV; HDV; driving behaviour; rain; snow; temperature; velocity; visibility; traffic safety

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PUBLIC INTEREST STATEMENT

Light conditions are important factors in traffic safety. If drivers cannot see the road properly, they cannot adjust their speed and slowdown in time to avoid accidents. However, the relationship between light conditions and vehicle speed is not fully understood and has rarely been studied for trucks. Drivers, in general, should drive faster in daylight or with road lighting and under good and clear weather conditions compared with driving in darkness and in rainy or snowy weather conditions. The article shows that under clear weather conditions, vehicle speed of trucks was not related to the light conditions. Truck speeds decreased in response to the amount of snowfall. Road lighting did not affect the truck speed in rainy or snowy weather.

1. Introduction

Trucks account for a disproportionate number of passenger vehicle deaths compared to other vehicle types (Lyman & Braver, 2003). Because of the high weight of trucks, collisions involving trucks have a high risk of serious consequences such as fatalities or severe injuries for persons travelling in other types of vehicles. In Sweden, for example, large trucks account for only 7% of the vehicle traffic but are involved in 20% of all road traffic accidents with fatalities (Engström, 2008; Vägverket, 2008). In the United Kingdom, heavy vehicles account for 1.3% of all registered vehicles but are involved in 18.3% of all accidents with fatal outcomes (Robinson, Watteerson, Dodd, Minton, & Gard, 2009). Similarly, in the Flemish region of Belgium in 2006, trucks accounted for 17.4% of vehicle kilometres on motorways, but 39.7% of the fatalities on the motorways involved at least one truck (De Winne & De Winne, 2009). In general, in the USA, in collisions involving trucks, 80% of the fatalities occur in the other vehicle (Stevens et al., 2001). Consequently, fatalities from truck accidents are often registered as fatalities in other types of vehicle. For example, in large-truck crashes in the USA, only 15% of fatalities occur in the large trucks while 77% of fatalities occur in the other vehicles involved (GAO, 2005; Jarossi, Matteson, & Woodrooffe, 2007). Because truck accidents cause such a large proportion of fatalities and are very damaging, it is important to understand the factors leading to such accidents in order to implement effective countermeasures.

One way to reduce the risk of accidents is to improve the light conditions while driving. A study in Greece has shown that the percentage of fatal accidents and severe injuries is almost twice as high for heavy vehicles operating in darkness compared to those operating in adequate light conditions. However, the study did not control for exposure, so it is not known how much lighting per se contributed to the accidents (Yannis, Kondyli, & Mitzalis, 2013). A study of 5889 fatal crashes involving trucks showed that crashes involving multiple-trailer trucks were more common under conditions of darkness, snow or ice on the road, and that higher speed limits (i.e. 104–120 km/h) as well as some other factors also played a role (Forkenbrock & Hanley, 2003).

In general, the risk of vehicle accidents increases with darkness (Beyer & Ker, 2009; Elvik, 1995; Johansson, Wanvik, & Elvik, 2009; Wanvik, 2009a). Thus, new or improved road lighting can reduce the number of fatal accidents (e.g. Fotios & Gibbons, 2018; Monsere & Fischer, 2008). Yet, the causal relationship between improved light conditions and the number of traffic accidents has rarely been studied for trucks. However, a comparison of the number of accidents five years before and after installation of road lighting on 125 roads in Norway showed that introducing road lighting resulted in a 54% reduction in the number of accidents involving heavy vehicles (Wanvik, 2009b).

The direct effect of light conditions on driving behaviour and traffic accidents is not yet fully understood. The effect of increased light conditions through road lighting may vary depending on, for example, the specific road environment (e.g. Fotios & Gibbons, 2018). In general, driving in darker conditions will result in reduced visibility with the result that drivers will detect objects too late to stop, or be unable to decrease their speed enough to reduce the energy of the impact when colliding. Driving in the dark is also associated with various perceptual errors, for example, lack of attention, distractions (Boyce, 2003), sleepiness, increased frequency of speeding, and alcohol consumption. Naturally, if visual conditions when driving are reduced, drivers should decrease their speed to adapt to the driving conditions. This was indirectly confirmed in a study by Assum, Bjørnskau, Fosser, and Sagberg (1999) showing that improved light conditions caused drivers to adjust their speed, resulting in 3–5% increase in vehicle speed in response to the introduced road lighting due to risk compensation (Assum et al., 1999).

Comparisons of vehicle speed between light and dark conditions, mostly involving passenger cars, have produced contradictory results. Increased vehicle speed in daylight has been shown (Assum et al., 1999; Bonneson, Pratt, Miles, & Carlson, 2007; Guzman, 1996; Möller, 1996) and lower vehicle speed in daylight has also been confirmed (Bassani & Mutani, 2012; De Valck, Quanten, Cluydts, & Berckmans, 2006). No significant differences in vehicle speed between darkness and daylight has also been demonstrated (Jägerbrand, Johansson, & Laike, 2018; Quaium, 2010). Observations of increased illuminance levels have been associated with increases in vehicle speed (Bassani & Mutani, 2012) and decreases in vehicle speed (de Bellis, Schulte-Mecklenbeck, Brucks, Herrmann, & Hertwig, 2018).

Similarly, driving simulator studies show both lower and higher speeds when comparing day and night scenarios (Bella & Calvi, 2013), and that reduced luminance can result in decreased driving speed (Pritchard & Hammett, 2012). No changes in speed patterns were observed in response to simulations of night and day conditions (De Valck et al., 2006). For passenger cars and trucks, the average night-time vehicle speed was shown to be lower than the average daytime speed. However, the speed decrease for trucks (1.6 km/h) was smaller than for passenger cars (3.2 km/h) (Bonneson et al., 2007).

In a previous study involving approximately 60 million vehicle passages of passenger cars we showed that vehicle speed depends on several independent factors. In clear weather conditions we confirmed trends as regards differences in average speed between daylight and darkness (i.e. higher speed in daylight with road lighting and lower in daylight on roads without road lighting), but could find no significant differences attributable to light conditions (e.g. daylight, twilight, darkness, and the presence of road lighting) (Jägerbrand & Sjöbergh, 2016). However, we found that vehicle speed decreased due to rain or snow and that the decrease was more substantial on roads without road lighting than on roads with road lighting.

Even though vehicle speed is highly essential to consider for traffic safety, no previous study has used large datasets to examine the combined effects of weather conditions, daylight, darkness and road lighting on the speed of trucks. Consequently, the aim of this study was to analyse truck speed to understand better how speed patterns are related to weather and light conditions.

In this study we investigated the following questions:

(I) if speed between brighter and darker conditions in clear weather will be different?

(II) if vehicle speeds are lower during rain and snow than in clear weather conditions? If so,

(III) if the speed reduction in rainy and snowy weather conditions is more substantial on roads without road lighting in darkness?

To investigate the questions, we used a large dataset of 5,344,287 vehicle passages by trucks. Of these, 3,659,940 passages were by light-duty vehicles and 1,684,347 passages by heavy-duty vehicles. We assumed that the speed responses of light-duty vehicles are similar to those of passenger cars in our previous study (Jägerbrand & Sjöbergh, 2016), whereas heavy-duty vehicles are often driven by experienced professional drivers who may drive more cautiously, especially during darkness and harsh weather conditions.

The data was extracted from hourly measurements on the Swedish road network at 25 locations for the period 2012-09-01 to 2014-05-31. Seventeen of the 25 locations were roads with road lighting. The data was cleaned to remove the impact of summer driving, congestions and specific hours of late-night driving where there is an increased occurrence of a few faster drivers because this could influence the results in a significant way in the study (Assum et al., 1999; Jägerbrand et al., 2018).

2. Materials and methods

2.1. Data collection

The data management phase started by locating the available data. Data on vehicle speed were collected from continuous measurements by the TF system of the Swedish Transport Administration (STA, 2013). TF measurements contain the date and time, vehicle speed for each vehicle, the vehicle class, and the total number of vehicles per class that pass the station. Data are collected all year around and stored on an hourly basis. Speed measurements are logged as the average speed for the measured hour and the average speed for each vehicle class. Measurements are performed using inductance loop detectors buried in the road (Metor 2000 light and 4000). Classifications of vehicles are based on the length and the mean amplitudes of the magnetic profiles. The vehicle classes used are personal cars, personal cars with trailer, light-duty vehicles, heavy-duty vehicles, light-duty vehicles with trailer, and heavy-duty vehicles with trailer. For this study, we extracted data for light-duty vehicles, heavy-duty vehicles, light-duty vehicles with trailer, and heavy-duty vehicles with trailer.

The TF stations used in our study were selected using Google Maps and its Street View function to determine whether road lighting was installed at a TF station. The date of the Street View was considered in the evaluation and we also checked with the Swedish Transport Administration to ensure that the road lighting was present during the time of the data collection. Seventeen locations with road lighting were selected in motorways, urban, residential, and rural roads (S1 Table, S2 Table, (Jägerbrand & Sjöbergh, 2016)). Eight TF stations without road lighting were both randomly and systematically chosen from the TF system and included as comparison. The TF stations without road lighting were included if they were close to any of the selected TF stations with road lighting (within the county) and if they had similar traffic patterns. It was, however, difficult to find unlit TF locations in comparable urban areas (with posted speed limits below 60–70 km/h), since the majority have road lighting. The eight TF stations finally included were on motorways or rural two-lane roads (S2 Table). Locations with low traffic volume (mainly rural roads in the countryside with different kinds of traffic patterns to larger roads) or high variation (e.g. centrally located high traffic roads) were systematically excluded.

Climate data were extracted from the Swedish Road Weather Information System (RWIS) (STA, 2011). The RWIS weather stations collect information every 30 minutes on temperature, air humidity, wind speed, wind direction and precipitation. We used data collected from the RWIS stations closest to each TF station and matched the data to cover the same time periods. If the closest RWIS station was malfunctioning, we used the second closest or used average values for two weather stations.

In this study, we include vehicle and weather data from 2012-09-01 to 2014-05-31. We excluded older data because the posted speed limits in many locations have changed.

Road characteristics such as road width and the posted speed limit were collected from the NVDB, the Swedish road database. Measurements of the distance to the nearest intersection were performed using Google Maps. A lighting engineer from the Swedish Transport Administration viewed the light poles in Google Maps Street View and estimated the age and quality of the road lighting. The timing of daylight, darkness, and twilight for each TF station was determined using data from the nearest city or village (S1 Table).

To pair the weather data (collected every 30 min) with the data from the TF stations (collected hourly), average measurements for the weather data that overlapped the 1-hour interval were used. The only exception was the "precipitation type", where 1 = no precipitation, 2 = rain, 3 = rain when the temperature is below freezing, 4 = snowfall, 6 = snowfall mixed with rain (in this case, the highest value of the measurements overlapping the 1-hour interval was used).

Data on daylight hours were collected as the hour of sunrise, the hour of sunset and whether there was midnight sun that day. In northern Sweden there are days when the sun never sets during the summer. Since we removed traffic data from the summer months, there were no days with midnight sun. Sunrise and sunset were determined in hours and minutes. We divided light conditions into "daylight", "darkness", and "twilight". Daylight was the hours between sunrise and sunset. We defined twilight as 30 minutes before sunrise and 30 minutes after sunset, unless the night was shorter than 30 minutes when the "daylight" condition would be given priority instead. Darkness was the hours after sunset and before sunrise that were not twilight hours.

Since a one-hour interval for traffic data may overlap more than one light condition, and possibly all three, we classified the one-hour intervals according to the light condition of the middle of the interval, that is, 30 minutes into the interval.

Data was reduced by removing data from the months of June, July and August because these three months have differing travel patterns and differences in the drivers using the roads compared to the rest of the year. The data was checked on an hourly basis to determine the approximate time and reveal whether traffic at any TF locations was queued due to rush hour traffic since these vehicles would not be free flowing. Vehicles are flowing freely when they have a minimum of 6 seconds headway in urban areas in Sweden (Vogel, 2002). Since the vehicle speed data used in this study is collected on an hourly basis, we could not exclude vehicles that were not free flowing as that would require data on the time or distance between vehicles. Instead, we made visual inspections and excluded typical rush hours (see below). We wanted to include daytime hours (daylight) and to compare them with dark time hours (darkness). We therefore used the hours 10:00–16:00 as representative of daytime periods that were less influenced by rush hours. It should be mentioned that in Sweden during parts of the year it can be dark even during midday hours (during the winter, in the northern parts), and it can be daylight even in night-time during the summers. We included the hours 18:00–22:00 to capture traffic from hours when it is typically dark. We excluded the hours 23:00–10:00 since some drivers drive very fast in those hours due to various reasons (see the introduction). Trucks in the EU are required to be equipped with speed limiters. In Sweden, these devices restrain trucks from driving above 80 or 90 km/h (depending on if they have trailers), but foreign-registered trucks may have different settings. Hence, it is uncertain that heavy-duty truck drivers drive faster at night, but it is likely that light-duty truck drivers are speeding. In addition, we wanted to exclude the morning rush to further ensure free flowing vehicles.

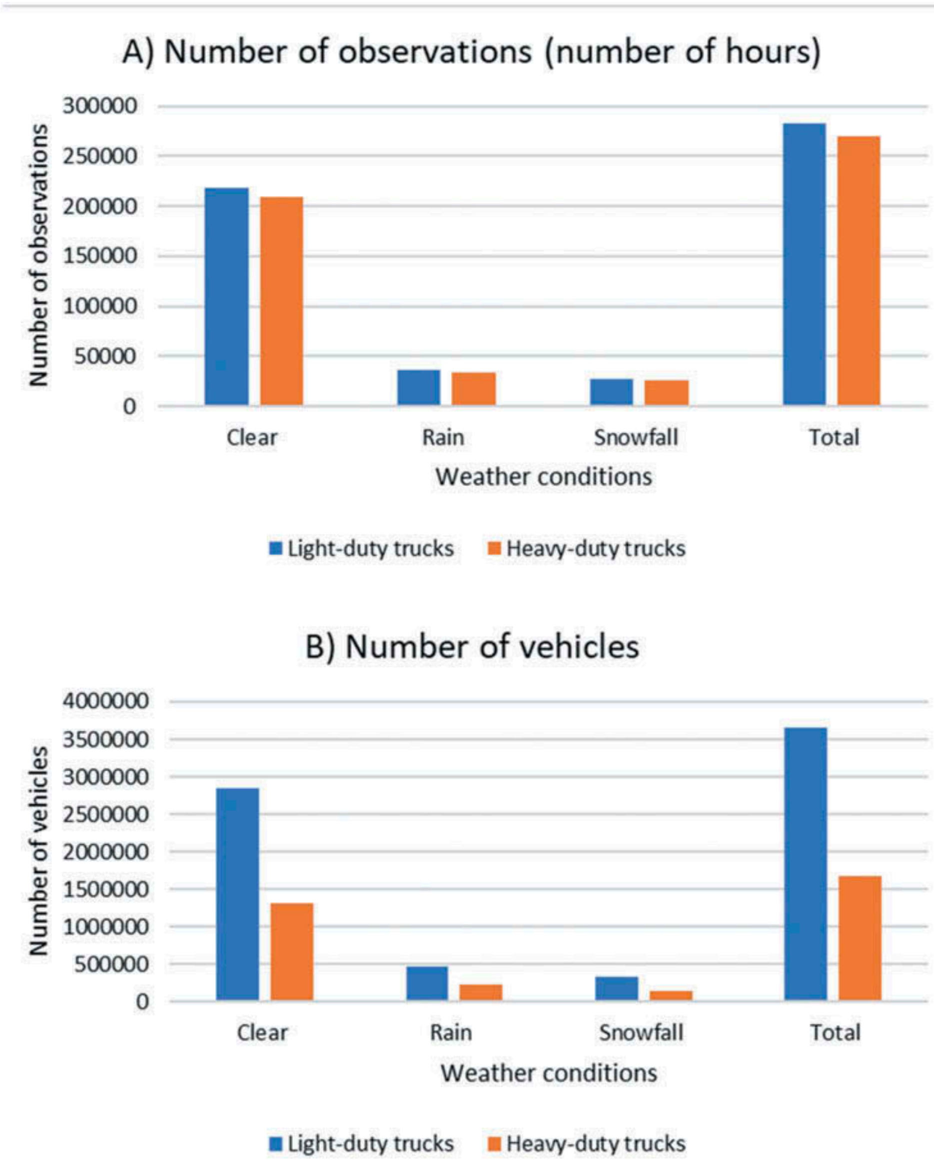
The final dataset consisted of a total of 5,344,287 truck passages, 4,158,845 passages in clear and dry weather, 706,289 passages in rain, and 479,153 passages in snow or a rain-snow mix (Figure 1).

2.2. Statistical analysis

The data were checked for normality and found to be very stratified, as would be expected due to the different posted speed limits for each of the roads and locations. The mean speed differences displayed a normal distribution but exhibited signs of strong heterogeneity and could not be transformed to reach homogeneity. Dividing the data into smaller subsets (for example, by weather conditions or light conditions or speed limits) did not improve the homogeneity. Therefore, it was not possible to use linear statistical methods to analyse the effects of independent factors on speed response variables. The data was relatively abundant in quantity and showed signs of having the character of big data, such as heterogeneity and spurious relationships, probably due to the many independent factors included, as also seen, for example, in (Gandomi & Haider, 2014). Our data was collected in the same locations and could therefore not be assumed to be uncorrelated. Behavioural adaptation or habituation may occur since it is likely that many drivers are driving the same route during the time-period included in the dataset and this could cause drivers to modify their behaviour in unknown ways (Intini, Colonna, & Olaussen Ryeng, 2019). In addition, some of our independent variables were likely to be correlated since they describe certain groups of roads (for example road width is connected to speed limit and type of road).

Consequently, we decided to use multivariate adaptive regression splines (MARS) (Friedman, 1991) to investigate the underlying structure of the data and to understand better how the many independent factors explained patterns in vehicle speed. MARS is a regression technique that can handle big data and is suitable for non-parametric regression because it can also handle correlations. MARS is more flexible than other regression techniques and build the models on partitioning

Figure 1. The number of observations/hours (A) and the number of vehicles (B) per weather condition for light-duty trucks and heavy-duty trucks .



the data into disjoint regions which allows various slopes produced by the hinge function for both linear and non-linear functions. For this process, MARS uses both forward and backward passes. The backward pass uses generalized cross validation (GCV) to compare subsets to identify the most optimal fit. The dependent variables we used were average speed and the speed difference, and we included the following independent variables: different light conditions (darkness, twilight, and daylight), distance to intersection, road width, posted speed limit, road surface temperature, year, month, presence or absence of road lighting, and precipitation.

Before analysis, the data were divided into three sets based on weather: clear, rain, or snow. MARS analysis was performed separately for each weather type. The analysis used the independent variables and any two-way interactions between them. Since R-squared is a statistical measure of how close the data are to the fitted regression line, we compared R-squared values to judge which model fitted the data better. This turned out to be the models using average speed (Table 1). The results from the MARS analysis show only the model with the highest R-squared values. Residual versus fitted plots were checked to evaluate whether the model had a reasonable fit.

Table 1. *Results of multivariate adaptive regression splines (MARS) analysis on average vehicle speed model*[1]*. GCV = generalized cross validation; RSS = residual sum-of-squares of the model; GRSq = 1-GCV/GCV.null; GCV.null is the GCV of an intercept-only model; RSq = R-Squared of the model. For more information see* (Milborrow, 2015)

Weather conditions			**Results**	
Vehicle class	**GCV**	**RSS**	**GRSq**	**RSq**
Clear				
Light-duty trucks	57	12,456,610	0.82	0.82
Heavy-duty trucks	48	9,991,093	0.83	0.83
Rain				
Light-duty trucks	64	2,288,770	0.81	0.81
Heavy-duty trucks	46	1,579,234	0.84	0.84
Snowfall				
Light-duty trucks	68	1,872,649	0.75	0.75
Heavy-duty trucks	57	1,517,429	0.76	0.76

[1] Model: dependent variable ~ light condition (daylight, darkness, twilight) + distance to the nearest intersection + road width + posted speed limit + road surface temperature + year + month + presence of road lighting or not + amount of precipitation

To investigate how speed was influenced by different light conditions (darkness, twilight, and daylight) we conducted Mann-Whitney U tests on relative differences between vehicle speeds for darkness-daylight, darkness-twilight, and twilight-daylight for road stretches (TF stations) with and without road lighting. The Mann-Whitney U test was performed separately for light-duty and heavy-duty trucks and for the three different weather conditions. MARS analyses were performed using R version 3.2.4-revised and the package "earth" (Milborrow, 2015). Mann-Whitney U tests were performed using IBM© SPSS© Statistics Version 25.

3. Results

3.1. Multivariate adaptive regression splines (MARS) analyses

The automatic variable selection performed by the MARS analysis showed that vehicle speed significantly depends on several factors depending on the different weather conditions (S3 Table). For clear weather conditions and light-duty trucks, the road width, posted speed limit, and the distance to intersections significantly influenced speed (both alone and in combination), and for heavy-duty trucks road lighting was also selected by the MARS analysis as significantly influencing speed (S3 Table, S1 Figure, S4 Figure).

Road width, distance to intersection and posted speed limit were chosen by the automatic variable selection as significantly influencing speed for both light-duty and heavy-duty trucks in rainy conditions (S3 Table, S2 Figure, S5 Figure). During snowfall, the same variables as well as the amount of snow (precipitation), the presence of road lighting and the month (month-4) were included for light-duty trucks as significant variables (S3 Table, S3 Figure). The amount of snow and the month were also included for heavy-duty trucks, but not the presence of road lighting (S3 Table, S6 Figure). MARS analyses chose not to use some variables. The month of the year was rarely included, and the light conditions (daylight, twilight, or darkness) were never included. Road lighting was only included in the analysis for clear weather conditions for heavy-duty vehicles as an significant interaction effect and during snow conditions for light-duty vehicles.

3.2. Speed differences in general

The vehicle speed on roads without road lighting shows that light-duty trucks drove somewhat faster during darkness than during daylight in clear weather (difference: 1.5 km/h) and rainy conditions (difference: 1.9 km/h) but faster in daylight than in darkness when driving in snowy conditions (difference: 1.5 km/h) (Table 2, Figure 2). The speed of light-duty vehicles was higher in darkness compared to daylight on roads with road lighting in rainy weather (difference: 1.3 km/h), while less difference was found between light conditions during clear weather and snowy conditions (Table 2). In general, speed differences attributable to darkness, twilight and daylight per se was not clearly shown by mean values and confidence intervals (Figure 2), except for snowy weather conditions and road lighting were speed in darkness was lower than in daylight for light-duty vehicles on highways with PSL of 110 km/h (Figure 2(f)).

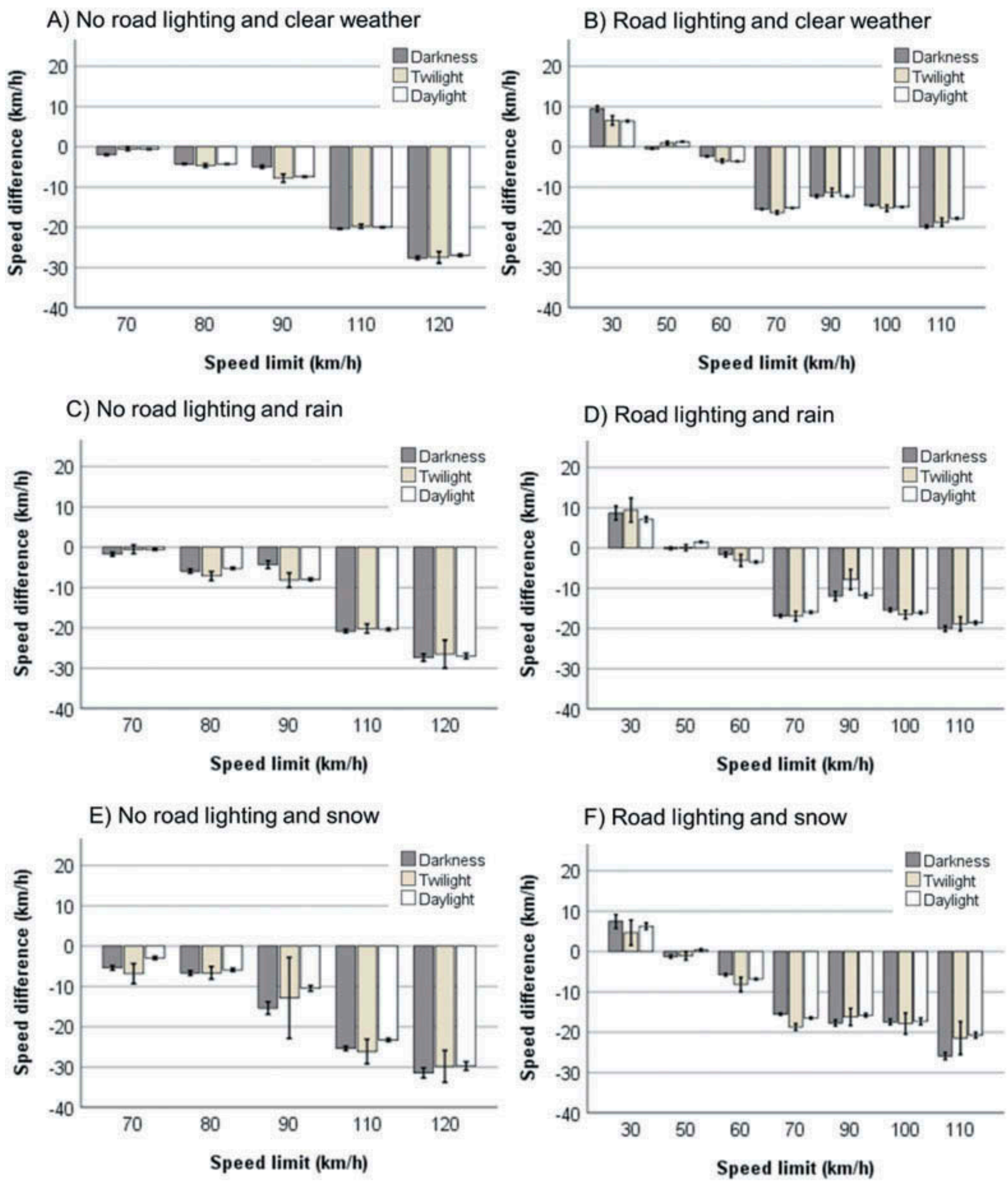
For the heavy-duty trucks, similar trends for higher vehicle speeds in darkness in clear and rainy weather conditions were found, although the difference seems very small, especially for roads without road lighting (Table 2, Figure 3). During snowfall, vehicle speed was generally higher during daylight for heavy-duty vehicle trucks and the difference was larger on roads without road lighting (Table 2, Figure 3(e), Figure 3(f)).

The speed difference for light-duty and heavy-duty trucks is highly dependent upon the speed limit (Figure 2, Figure 3). Decreases in vehicle speed is clearly visible for all conditions with higher speed limits such as rural roads and highways (Figures 2 and 3).

Table 2. Mean values (km/h) and standard deviation (SD) for vehicle speed of light-duty and heavy-duty trucks on roads with and without road lighting for different weather conditions (clear, rain, and snowfall), and for darkness, twilight, and daylight hours. N = 5,344,287 (total vehicle passages)

Weather condition	No road lighting (n = 8)		Road lighting (n = 17)	
	Mean	SD	Mean	SD
Light-duty truck speeds (km/h)				
Clear				
Darkness	84.2	9.7	64.8	16.9
Twilight	83.1	9.9	63.8	17.2
Daylight	82.7	9.8	65.2	16.9
Rain				
Darkness	84.3	9.6	69.4	18.0
Twilight	82.5	10.1	70.4	17.7
Daylight	82.4	10.0	68.1	17.5
Snow				
Darkness	79.6	10.6	59.5	14.5
Twilight	77.4	13.0	55.4	13.5
Daylight	81.1	10.1	59.8	14.9
Heavy-duty truck speeds (km/h)				
Clear				
Darkness	83.2	7.3	70.3	16.1
Twilight	82.5	7.6	69.4	16.6
Daylight	82.4	7.8	70.2	16.0
Rain				
Darkness	83.1	7.1	75.3	14.8
Twilight	82.2	8.2	75.8	14.2
Daylight	82.2	8.0	73.5	15.4
Snow				
Darkness	79.6	8.7	63.5	15.2
Twilight	77.0	11.1	58.1	15.2
Daylight	81.5	8.2	64.0	16.0

Figure 2. Speed differences of light-duty trucks. Mean values of speed difference for light-duty trucks, i.e. the measured average speed minus the posted speed limit, plotted against posted speed limit (km/h) separately for roads without and with road lighting for different light conditions (darkness, twilight, daylight), and in different weather conditions (clear, rain, snow). Mean values ± 95% confidence interval.



3.3. Speed differences for specific road stretches

Calculations based on relative differences on specific road stretches (TF stations) showed that vehicle speed for light-duty trucks on roads with road lighting was higher (0.2–0.5%) in darkness compared to daylight in clear and rainy weather conditions and lower in darkness compared to daylight in snowfall conditions (2.8%) (Table 3, S4 Table, S5 Table). A similar trend was found for vehicle speed on roads without road lighting: the speed was 0.3–0.6% higher during darkness in clear and rainy weather conditions and 1.5% lower in darkness compared to daylight during snowfall conditions (Table 3, S4 Table, S5 Table).

Comparisons of relative speed reveals that speed is lower on roads with road lighting for 70 km/h (one rural road without road lighting and three urban roads with road lighting) and 90 km/h (only rural roads) in clear weather and somewhat higher with road lighting on roads with 110 km/h (only highways) (Figure 4). Snowy weather conditions reduce vehicle speed and the reduction is more clearly seen on roads without road lighting (Figure 4).

Figure 3. Speed difference of heavy-duty vehicle trucks. Mean values of speed difference for heavy-duty trucks, i.e. the measured average speed minus the posted speed limit, plotted against posted speed limit (km/h) separately for roads without and with road lighting for different light conditions (darkness, twilight, daylight), and in different weather conditions (clear, rain, snow). Mean values ± 95% confidence interval.

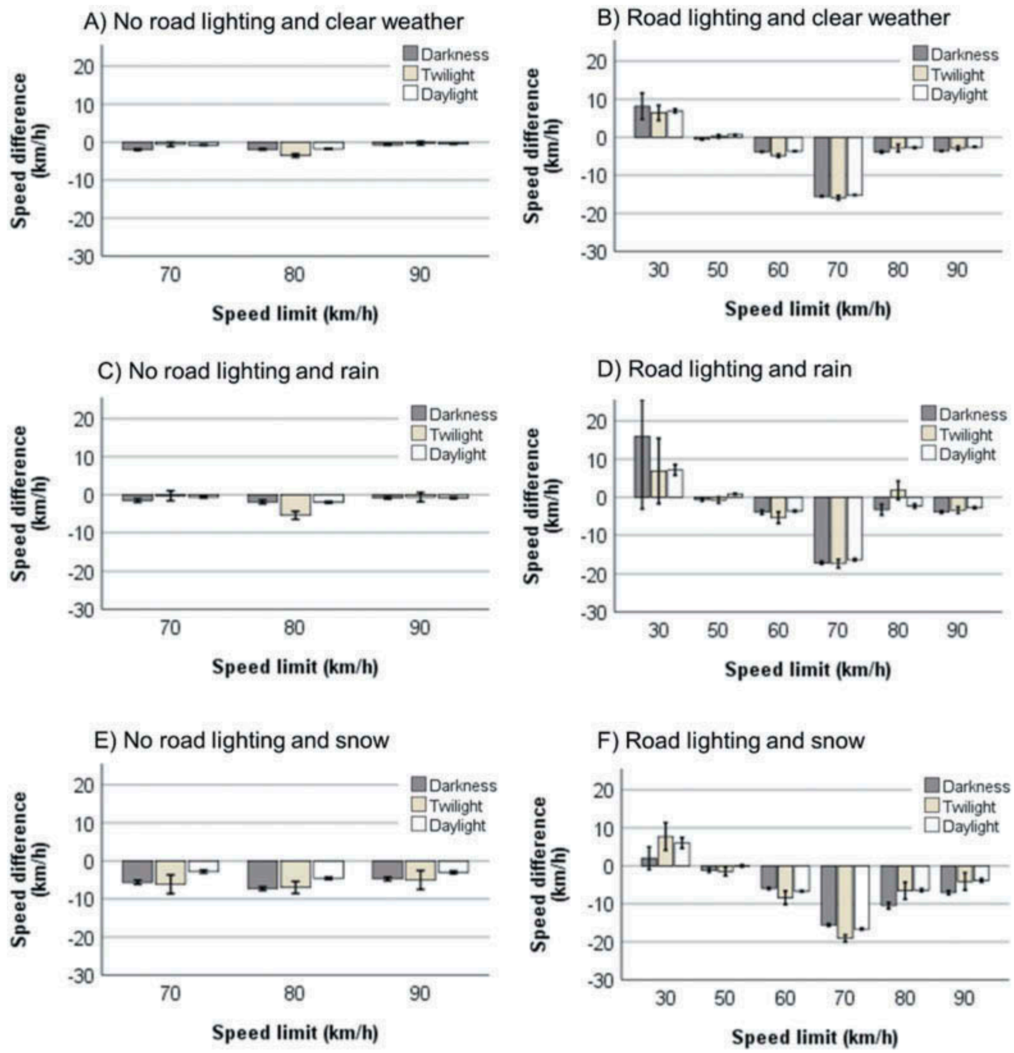


Table 3. The speed of light-duty trucks. The relative speed difference between darkness and daylight in average speed (km/h) and percentage difference (%) based on specific road stretches (TF stations), without or with road lighting and in different weather conditions. Average posted speed limit (PSL). No significant differences were revealed by Mann-Whitney U test			
Weather and light conditions	**PSL (km/h)**	**Speed difference Darkness—Daylight**	
		km/h	**%**
Without road lighting			
Clear	68.8	0.2	0.6
Rain	68.8	0.1	0.3
Snowfall	68.8	−1.1	−1.5
With road lighting			
Clear	90	0.4	0.5
Rain	90	0.3	0.2
Snowfall	90	−2.4	−2.8

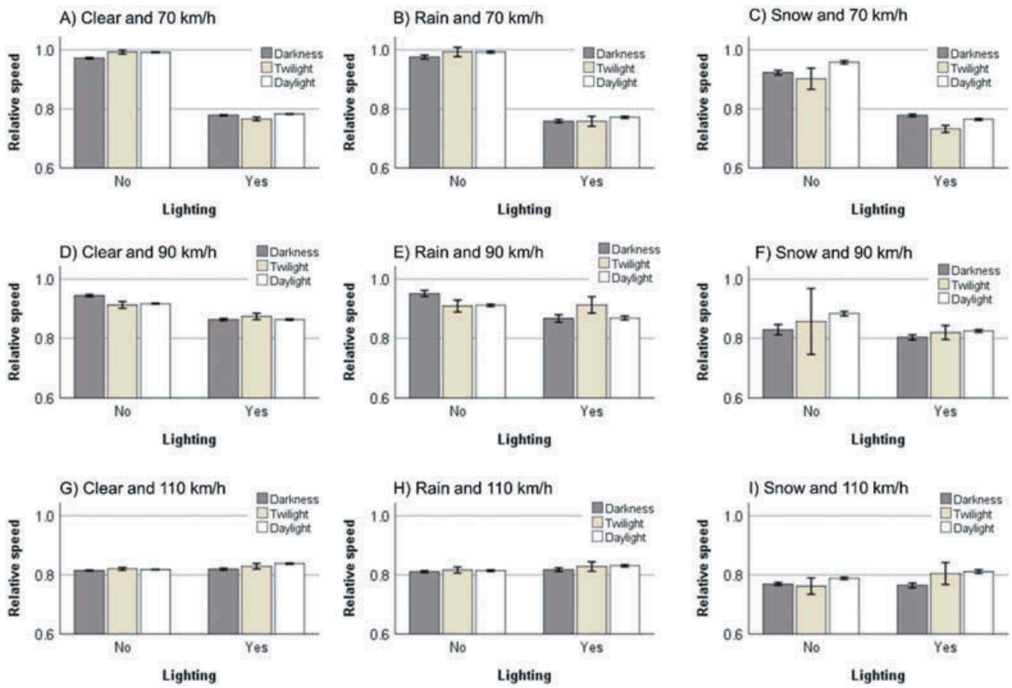


Figure 4. Relative speed of light-duty trucks. Mean values of relative speed for light-duty trucks, i.e. the measured average speed divided by the posted speed limit without and with road lighting separately for roads of the same speed limits (70, 90, 110 km/h) for different light conditions (darkness, twilight, daylight), and in different weather conditions (clear, rain, snow). Mean values ± 95% confidence interval.

For heavy-duty trucks, speed was higher in daylight conditions (Table 4, S4 Table, S5 Table, Figure 5). During snowfall vehicle speed for heavy-duty trucks was substantially higher during daylight (for roads with road lighting and without road lighting, 3.2% and 3.0%, respectively) (Table 4, Figure 5).

Again, comparisons of relative speed reveals that speed is lower on roads with road lighting for 70 km/h (Figure 5). Relative speed for clear and rainy weather conditions for 80 km/h and 90 km/h is not very different between roads without and with road lighting and in different light conditions (Figure 5) and confirms previous findings. In snowy conditions, speed is reduced in darkness compared to daylight both without and with road lighting for 80 km/h and 90 km/h (Figure 5).

The relative differences in vehicle speed in Tables 3 and 4 were tested by the Mann-Whitney U test and no significant differences were revealed.

Table 4. The speed of heavy-duty trucks. The relative speed difference between darkness and daylight in average speed (km/h) and percentage difference (%) based on specific road stretches (TF stations), without or with road lighting and in different weather conditions. Average posted speed limit (PSL). No significant differences were revealed by Mann-Whitney U test

Weather and light conditions	PSL (km/h)	Speed difference Darkness—Daylight	
		km/h	%
Without road lighting			
Clear	64.7	−0.9	−1.3
Rain	64.7	−0.5	0
Snowfall	64.7	−1.8	−3.2
With road lighting			
Clear	81.3	0	0
Rain	81.3	−0.1	−0.2
Snowfall	81.3	−2.8	−3.5

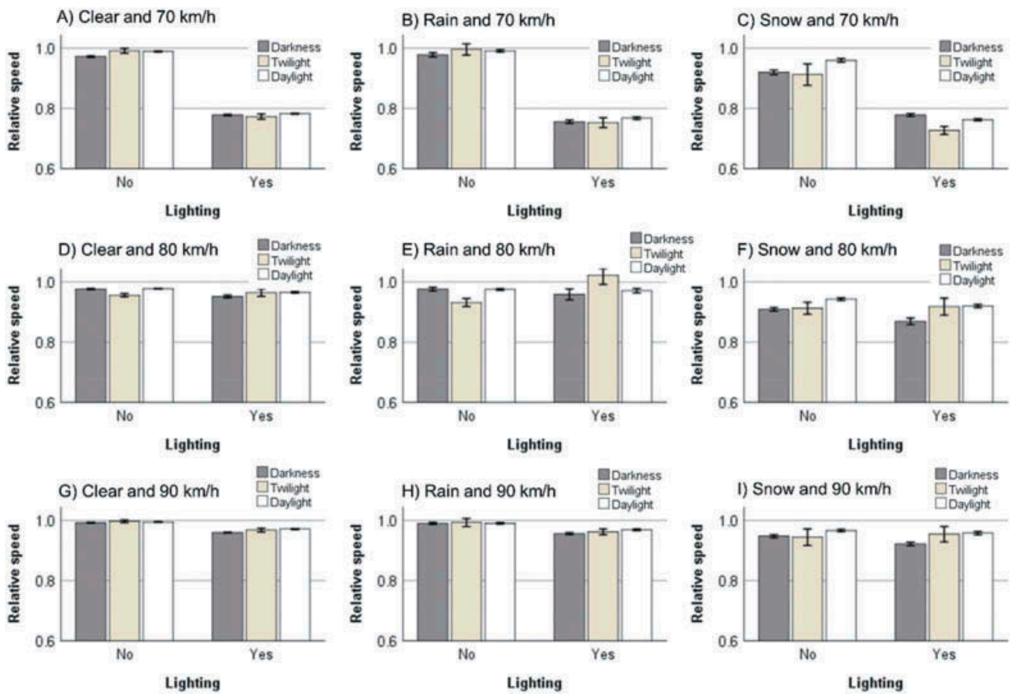


Figure 5. Relative speed of heavy-duty vehicle trucks. Mean values of relative speed for heavy-duty trucks, i.e. the measured average speed divided by the posted speed limit, without and with road lighting separately for roads of the same speed limits (70, 80, 90 km/h) for different light conditions (darkness, twilight, daylight), and in different weather conditions (clear, rain, snow). Mean values ± 95% confidence interval.

4. Discussion

Speed differences between brighter and darker conditions in clear weather showed that the average speed for light-duty vehicles and heavy-duty vehicles was 1.5 km/h and 0.8 km/h higher in darkness than in daylight on roads without road lighting. The MARS analysis did not include light conditions (darkness, daylight or twilight) in the automatic variable selection, indicating that light conditions did not contribute significantly to the speed responses. However, the MARS analysis did include road lighting in clear weather for heavy-duty trucks as an interaction effect but the speed differences seemed to be small. Yet, when statistically analysing the relative differences between speed in darkness and in daylight on the same road stretches without lighting, we found no significant differences in the speed responses of either light-duty or heavy-duty trucks. Speed responses for heavy-duty trucks were 0.9 km/h higher in daylight than in darkness in clear weather conditions without road lighting, which is the opposite of the trends for the whole dataset.

Relating our findings to question I, if speed is affected by brighter or darker conditions, we can confirm the existence of detectable speed differences in the overall truck dataset, with higher speeds in darkness on roads without road lighting in clear weather conditions. However, the differences were not significant enough to be selected in the statistical analyses and were not clearly visible when analysing relative differences on specific road stretches. Thus, we did not find any conclusive evidence of consistent patterns of speed differences with respect to lighting conditions (darkness, daylight, twilight or road lighting) under clear weather conditions. Trends of higher speed in darkness on roads without road lighting under clear weather conditions were found for passenger cars and, as in this study, the differences could not be statistically confirmed (Jägerbrand & Sjöbergh, 2016).

The lack of a clear and significant speed response to brighter conditions has been shown previously (Quaium, 2010), but the opposite pattern, that speeding increases when light decreases has also been shown based on a large dataset for roads with 30–50 km/h speed limits (de Bellis et al., 2018). In our study, the truck speed responses on 30 km/h and 50 km/h roads is somewhat different compared to roads with other speed limits, for example, vehicle speed on 30 km/h roads is always above the posted speed limit. This could explain the difference between our study and de Bellis et al. (2018), although our data is restricted to trucks, so it is difficult to compare responses. However, a lack of clear response to brighter conditions has also been found in studies that have removed the effect of confounding factors such as rush hour, or typical night-time driving behaviour from the analysis (Jägerbrand et al., 2018; Jägerbrand & Sjöbergh, 2016), and when the analysis of speed responses is based on big data (Jägerbrand & Sjöbergh, 2016). Night-time driving is associated with a change in driver groups and an increased occurrence of a few faster drivers and may also include factors such as sleepiness (e.g. Assum et al., 1999) and risky behaviour. It is therefore important to exclude typical night-time driving behaviour to focus on speed responses to light conditions per se but doing so can result in weaker speed "responses" to the light conditions compared to other studies.

Speed generally decreased during snowy conditions for both light-duty and heavy-duty trucks. However, the average speed during rainy conditions was quite similar to the speed in clear weather conditions on roads without road lighting, which may indicate that truck drivers do not perceive rainy conditions as a traffic safety risk. The difference in speed responses to harsher weather conditions was not significantly different when analysed on specific road stretches, although the speed reducing impact of snowy weather conditions was clearly visible in figures of speed differences and relative speed for different speed limits. As the amount of precipitation (and snow as precipitation) was included as a variable in the MARS automatic selection, it is probably the amount of snowfall that determines the speed response rather than the mere presence of snow. We conclude, for question II (if speed is reduced in rainy and snowy conditions), that trucks decrease speed in response to snowfall but not to rain, and that the response to snowfall is dependent upon the amount of snow. It is likely that the friction values under snowy conditions cause drivers to slow down since truck drivers are usually aware of the higher risk of accidents under such conditions (e.g. jack-knifing). Friction values are lower in snowy conditions than in rainy conditions, causing trucks to have very long braking distances due to their heavy weight (Kordani, Rahmani, Nasiri, & Boroomandrad, 2018). At speeds above 80 km/h, the risk of hydroplaning is high for trucks. The lower values of friction under rainy conditions are probably highly related to rain intensity. In this study we had no information on friction values and the weather data were collected from stations that were not situated directly at the site of the vehicle speed measurements. It is therefore difficult to draw any conclusions regarding possible friction values and the speed of the trucks. Nevertheless, the currently available technology could be used to provide truck drivers with real-time information on the friction percentage on the roads (Colonna, Berloco, Intini, Perruccio, & Ranieri, 2016), which also have high relevance for friction-adapted automated truck driving with fewer human errors (Colonna, Intini, Berloco, & Ranieri, 2018).

Comparisons of the speed responses of trucks in rainy conditions reveal little difference compared to clear weather. In snowy weather, light-duty trucks, in general, tend to drive faster in daylight than in darkness but the percentage difference in speed between roads with and without road lighting is small. For heavy-duty trucks, the speed difference between darkness and daylight is more substantial when speeds on roads with road lighting are compared to speed on roads without road lighting (2.8% and 1.5% respectively). Thus, our results regarding question III, shows that that the speed reduction in rain and snow weather conditions is not more substantial on roads without road lighting in darkness.

For passenger cars, a decrease in vehicle speed on roads without road lighting during snow weather conditions has been more clearly shown (Jägerbrand & Sjöbergh, 2016). The differences between the speed responses of trucks and passenger cars may be that trucks are less dependent on light conditions for visual performance since they have stronger headlights. Driving heavier vehicles such as trucks also makes it less likely to respond in speed to small variations in the traffic conditions such as rain or snow, unless the weather is extreme. In most roads included in this study, vehicle speed of trucks was below the posted speed limit and there were small variations due to weather or light conditions, while there are large differences between different roads and speed limits.

A conclusion from this study is that the lack of clear differences in vehicle speed between different weather conditions (darkness, daylight and twilight) may indicate that most truck drivers, like drivers of passenger cars (Jägerbrand & Sjöbergh, 2016), do not adjust their speed to compensate for the decreased reaction time to avoid traffic accidents. Drivers tend to fail to compensate fully for low light conditions since they misjudge their visual ability in darkness (e.g. Owens, Wood, & Owens, 2007). However, average speed of trucks in this study was most often well below the posted speed limits and driving in snow decreased the speed even further. Together with the fact that speed difference between darkness and daylight was quite small, do not suggest that this was the case. Nevertheless, we do not know how valid our results are for such generalizations since we removed some speed data from the dataset.

Future studies may investigate speed responses to various light conditions and road environments under more controlled circumstances, in order to examine driver responses in more detail. Especially speed adjustment under various conditions would be interesting to study. Increased light conditions during driving, such as road lighting, do not necessarily mean that traffic safety will automatically increase but needs to be carefully examined together with other factors to better understand whether light is a significant factor influencing speed and safety in the specific road environment (e.g. Fotios & Gibbons, 2018; Fotios & Price, 2017).

A potential drawback influencing the results in this study is that the road stretches chosen were not randomized in the road network, as we used existing measurements points/stations. This may affect the data and cause bias. For example, the roads with and without road lighting have different posted speed limits, making it impossible to compare mean values. This results in that conclusions must be drawn based on relative differences instead.

This study did not contain a direct measurement of safety in relation to light conditions but used vehicle speed as a surrogate for driving behaviour. Thus, we cannot directly connect safety and risk to our study. To perform such a study, values for the risk of collisions with differences in lighting and weather and at different speed limits would have to be known. For example, accident risk is dependent upon exposure, so it is important to include travel data or traffic flow when analysing such things as accident rates (Blower, Campbell, & Green, 1993; Jovanis & Delleur, 1983; Khasnabis & Assar, 1989).

The results for twilight are less stable than those for darkness and daylight since there were fewer hours with this light condition. In addition, even though we tried to remove traffic rush hours and queuing, the vehicles could not be regarded as truly free flowing. It is known that vehicle speed is affected by vehicles travelling ahead, but the data we used do not contain information on this point. Another aspect is the influence of distance to intersections which varied somewhat for the road stretches. This is something we will consider in future studies of the same dataset.

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Data availability statement
All datafiles are available from github.com repository at: https://github.com/jonas-work-tng/trucks-weather-lighting

Supplemental Material
Supplemental data for this article can be accessed here.

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