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# Exploration of the characteristics and trends of electric vehicle crashes: a case study in Norway

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**ORIGINAL PAPER**

# Exploration of the characteristics and trends of electric vehicle crashes: a case study in Norway

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## Abstract

With the rapid growth of electric vehicles (EVs) in the past decade, many new traffic safety challenges are also emerging. With the crash data of Norway from 2011 to 2018, this study gives an overview of the status quo of EV crashes. In the survey period, the proportion of EV crashes in total traffic crashes had risen from zero to 3.11% in Norway. However, in terms of severity, EV crashes do not show statistically significant differences from the Internal Combustion Engine Vehicle (ICEV) crashes. Compared to ICEV crashes, the occurrence of EV crashes features on weekday peak hours, urban areas, roadway junctions, low-speed roadways, and good visibility scenarios, which can be attributed to the fact that EVs are mainly used for urban local commuting travels in Norway. Besides, EVs are confirmed to be much more likely to collide with cyclists and pedestrians, probably due to their low-noise engines. Then, the separate logistic regression models are built to identify important factors influencing the severity of ICEV and EV crashes, respectively. Many factors show very different effects on ICEV and EV crashes, which implies the necessity of re-evaluating many current traffic safety strategies in the face of the EV era. Although the Norway data is analyzed here, the findings are expected to provide new insights to other countries also in the process of the complete automotive electrification.

**Keywords:** Electric vehicle crash, Logistic regression, Crash severity, Low noise

## 1 Introduction

Motor vehicle crashes are one of the leading causes of unintentional injuries and deaths in the world. Exploring characteristics of crashes to develop effective counter-measures is one of the primary duties for transportation agencies. Numerous studies have been conducted to analyze motor vehicle crashes from various aspects. However, most of them target at conventional internal combustion engine vehicles (ICEVs), while only few aim at emerging electric vehicles (EVs). EVs have increased fast in the past 2 decades and are expected to replace

ICEVs gradually in the future. Therefore, it is time to explore the features and trends of EV crashes now.

Transportation is a major energy consumer and emission producer, and motor vehicles take the lead in this sector. According to the International Energy Agency [1], passenger cars and freight road vehicles consumed about 32% of final energy globally and accounted for almost a third of final energy-related $CO_2$ emissions in 2017. Therefore, a fundamental component for achieving sustainable development is to establish a sustainable transportation system, in which it is essential to replace conventional ICEVs with more energy-efficient and emission-reducing EVs. According to the degree of electricity used as the energy source, EVs can be categorized into three types: (1) hybrid electric vehicles (HEVs), powered by conventional gasoline or diesel ICEs and an electro-motor using energy from the batteries on board, which

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is filled in by ICEs; (2) plug-in hybrid electric vehicles (PHEVs), powered by conventional gasoline or diesel ICEs and electromotors using energy from the batteries on board, which could be recharged from the power grid; (3) battery electric vehicles (BEVs), propelled by electromotors using the electric energy stored in batteries onboard the vehicle, which are recharged from the power grid (at home or at street/shop charging stations) [2].

In 2019, around 2.2 million passenger BEV (74%) and PHEV (26%) sales globally translated into an average of 2.5% market share [3]. Currently, many countries have proposed their timelines of phasing out the fossil ICEVs in the auto market [4]: Norway, 2025; Denmark, 2030; Netherlands, 2030; Israel, 2030; Sweden, 2030; UK, 2032/2035; and France, 2040. In the context of automotive electrification, Norway has been leading the world. In 2019, 56% of Norway's vehicle sales were plug-in vehicles (including 42% of BEVs) [5]. As a comparison, the proportion was 5.2% in China, 3.2% in UK, 2.9% in Germany, 2.8% in France, 2.7% in Canada, and all other car markets with over 1 million total sales shared 2% or less. At the beginning of 2020, the number of registered electric passenger cars has reached up to 487,429 in Norway, occupying 17.3% of total registered passenger cars [6].

With the increase of on-road EVs, EV safety has been becoming a new concern. Compared to ICEVs, vehicle electrification brings many new challenges to traffic safety. However, existing research on EV safety, especially those based on real-world EV crash data, are quite limited globally, which kind of hinders agencies to come up with effective countermeasures. With traffic crash data of Norway from 2011 to 2018, this study is designed to accurately reveal the unique features and trends of EV crashes. The findings are expected to provide new insights on addressing safety issues of EVs to not just Norway, but also the whole European community.

The rest of the paper is organized as follows. Section 2 is the literature review. Section 3 introduces the materials used in this study. Section 4 conducts a statistical analysis to identify the factors significantly influencing the severity of EV crashes. Section 5 concludes the main findings and discusses the limitations of this study.

## 2 Literature review

Safety performance is a vital factor of influencing the expansion of EVs [7–9]. The primary safety concern to EVs is their threat to pedestrians and bicyclists due to their silent engines, especially for visually impaired ones under low-speed scenarios [10–16]. When ICEVs are approaching pedestrians/bicyclists, the engine noise is expected to effectively provide alerts. However, the silent operation of EVs with electric motors, which is an advantage in terms of comfort [17, 18], augments the odds of conflicts between EVs and pedestrians/bicyclists. Hanna [19] analyzed the pedestrian and bicyclist crashes involved in some HEVs and ICEVs in 12 states of the U.S., and found that HEVs had a higher incident rate in pedestrian or bicyclist crashes than ICEVs. Later, Wu et al. [16] updated the study with the crash data from 16 states of the U.S. in a longer period. Similar findings were provided that the odds of an HEV involved in a pedestrian or bicycle crash is 35% or 37% greater than that of an ICEV, respectively. In a simulation study, EVs were found to pose a 25% higher near-crash risk to pedestrians than ICEVs [20].

Another safety concern is EVs are prone to associate with risks of fire, electric shock, and fuel tank rupture in case of lithium-ion batteries getting overheated or collisions [21]. They bring many new difficulties to rescue operations: (1) the conventional extinguishers might not work in the face of fires from lithium-ion batteries [22]; (2) battery packs, broken or not, may still have stored energy even after a fire, which can be potentially dangerous and easily reignited [23, 24]; and (3) quiet electric motors make it difficult to figure out whether they are on or off, which poses a huge threat to responders.

In addition, vehicle crash features are highly related to their usage patterns, which may be very different for ICEVs and EVs. A recent study shows that the median annual household incomes of ICEV owners and BEV owners in the U.S. are $75,000 and $200,000, respectively [25]. The huge income discrepancy means that owners of ICEVs and EVs may have very different occupations, travel patterns and driving preferences, leading to different crash features. Therefore, it is hard to directly infer the features of EV crashes based on the understandings of ICEV crashes. However, due to the limited EV crash data, most existing studies explore safety performance of EVs by theory analysis [26], crashworthiness testing [27], experiment driving [28], simulation [20], or analysis of alternative vehicles [29], rather than analyzing the real-world crash data. Although these studies provide many insights on understanding the EV safety, it is far from enough to get a full picture without analyzing the real-world EV crashes. Hanna [19] and Wu et al. [16] analyzed HEV crashes involving pedestrians and bicyclists in the U.S. However, their data might be outdated (all crashes occurred before 2009) to represent the current EV crashes considering the rapid growth of EVs in the past decade. Chen et al. [30] analyzed hybrid and electric vehicle crashes with crash data from 2009 to 2013 in the U.S, but their data only contained 20 EVs, which is too small to provide solid conclusions.

As a summary, there is lack of studies of exploring the characteristics and features of EV crashes with the real EV crash data. An extensive investigation to EV crashes

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with the large, updated, and complete crash data is urgently required.

## 3 Materials

Norway is a Nordic country with the area of 385,207 square kilometers and a population of 5,312,300 (as of August 2018) [31]. Traffic crash data of Norway from 2011 to 2018 were obtained from the Norwegian Public Roads Administration (NPRA), and roadway traffic volumes (i.e., vehicle kilometers per year) were retrieved from Statista [32] and Statistics Norway [33]. It can be found that EV road traffic volumes had been increasing in Norway (Fig. 1), leading to the increasing EV crashes (Fig. 2). Here, an EV crash means at least a PHEV or BEV is involved in the crash. The EV crash count was zero in 2011, but reached up to 112 in 2018, occupying 3.11% of total crashes. Totally, 35,441 ICEV crashes and 342 EV crashes occurred in the survey period. Based on the available information, some descriptive analyses are conducted to understand basic features of EV crashes. It should be noted that driver demographic factors are not discussed here, since they are unavailable in our dataset due to the privacy concern.

### 3.1 Are EV crashes more severe?

In terms of traffic safety, a primary concern to transportation agencies is whether EV crashes are more severe than ICEV ones. In Norway, traffic crashes are recorded as five types by severity: killed, very seriously injured, seriously injured, slightly injured, and not specified. Table 1 shows distributions of crashes by severity. Considering the imbalanced distributions, crashes are redivided into two categories: (1) severe, which combines killed, very seriously injured, and seriously injured; and (2) light, which refers to slightly injured and not specified. The new categorization would be used in the following analysis.

A Pearson's chi-squared test [34, 35] is used to check whether the severity distributions of EV and ICEV crashes significantly differ from each other. The p-value of the test statistic is 0.289, and the 95% confidence interval of the difference of the two proportions is (−0.004, 0.001). Therefore, at the 95% confidence interval, the crash severity distributions of EVs and ICEVs do not show statistically significant differences.

### 3.2 When do EV crashes occur?
#### 3.2.1 Day of week

Travel patterns of people vary by day of week. Here, an EV crash means at least a PHEV or BEV is involved in the crash. Besides, compared to ICEV crashes, the proportion of EV crashes on weekends is obviously smaller: 17.6% for EVs versus 24.1% for ICEVs. Since travels are dominated by commuting trips on weekdays and discretionary trips on weekends, it implies that EVs might be used more for commuting trips comparing to ICEVs (Fig. 3).



**Fig. 1** EV road traffic volumes and their proportions in total road traffic volumes in Norway per year (2011–2018)

**Fig. 2** EV crash counts and their proportions in total crashes in Norway per year (2011–2018)
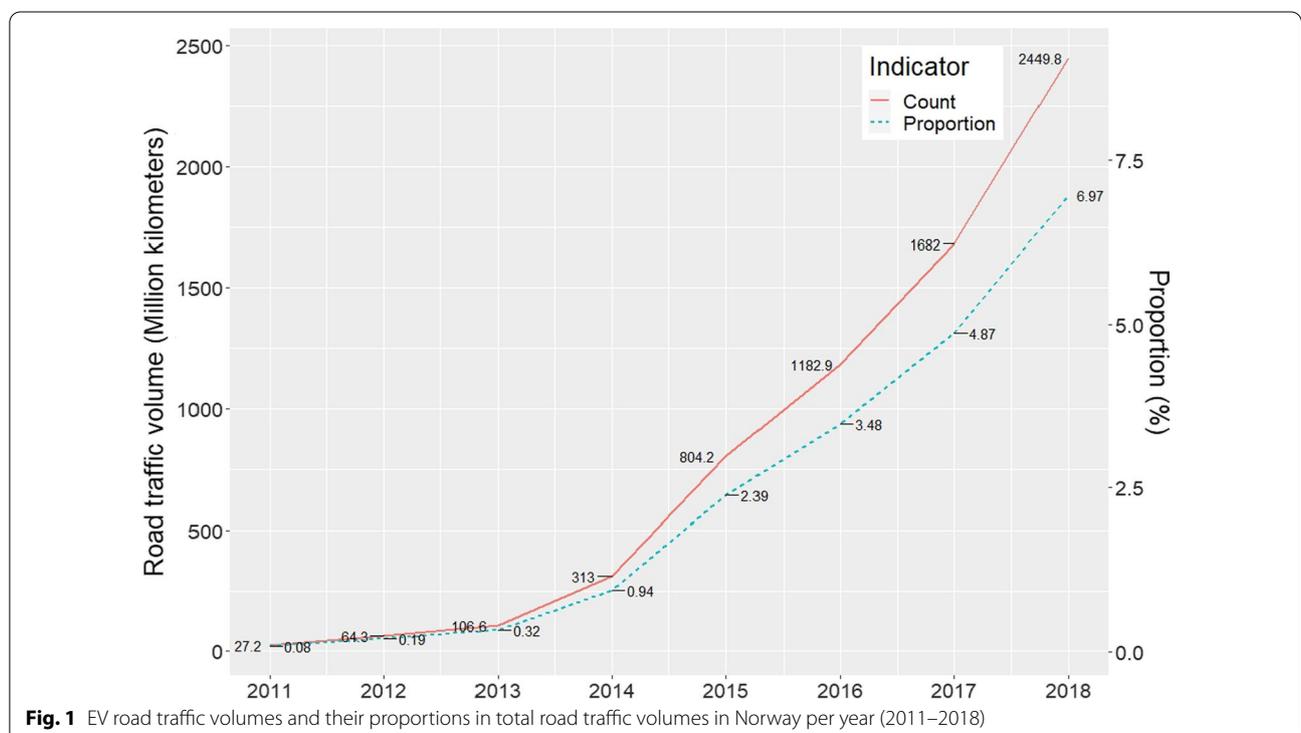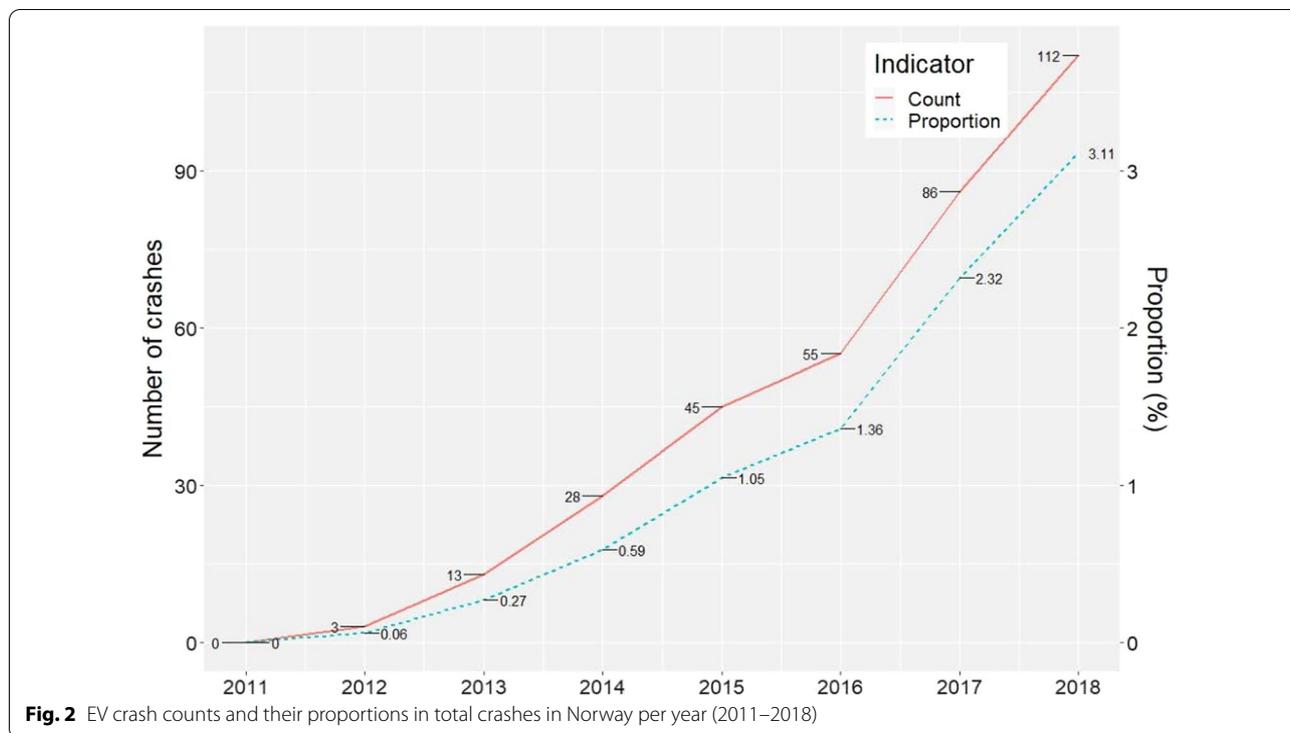
**Table 1** Distributions of crashes by severity

| Categorization | Severity | ICEV (%) | EV (%) |
|---|---|---|---|
| Old | Killed | 2.7 | 1.8 |
| | Very seriously injured | 1.1 | 0.8 |
| | Seriously injured | 11.0 | 9.9 |
| | Slightly injured | 82.4 | 84.5 |
| | Not specified | 2.9 | 2.9 |
| New | Severe | 14.8 | 12.6 |
| | Light | 85.2 | 87.4 |

### 3.2.2 Time of day

As shown in Fig. 4, both ICEV and EV crashes present the clear morning peak (7:00–9:00 a.m.) and afternoon peak (3:00–6:00 p.m.). Besides, compared to ICEV crashes, EV crashes occur more often at the two peaks: 15.5% in the morning peak and 32.5% in the afternoon peak for EV crashes, compared to 10.4% in the morning peak and 26.2% in the afternoon peak for ICEV crashes. Meanwhile, there are very few EV crashes at nighttime (7:00 p.m. to 6:00 a.m.). It confirms that EVs might be mainly used for commuting.

## 3.3 Where do EV crashes occur?
### 3.3.1 Settlements

Table 2 shows distributions of crashes by settlements: half of EV crashes occurred in urban areas, whereas this proportion is only one third for ICEV crashes. This imbalanced distribution may be explained as the following reasons: (1) EVs are popularized and introduced into the market from urban areas [36]; (2) The significant amount of public supporting infrastructure such as recharging facilities in urban areas reassure EV drivers; (3) Many incentives for EVs, such as free parking, exemption from road tolls, and access to bus lanes, might be only meaningful for urban car-commuters; and (4) As shown previously, EVs are mainly used for daily commuting, which is common for urban residents, but not necessarily for rural residents.

### 3.3.2 Speed limit

Table 3 shows the distribution of crashes by speed limit: 66.5% of ICEV crashes and 80.7% of EV crashes occurred on low and middle-speed (< 80 km/h) roadways, whereas 32.5% of ICEV crashes and 19.3% of EV crashes occurred on high-speed ($\geq$ 80 km/h) roadways. That is, compared to ICEV crashes, EV crashes are less likely to occur on high-speed roadways. It is also understandable as high-speed roadways in Norway are

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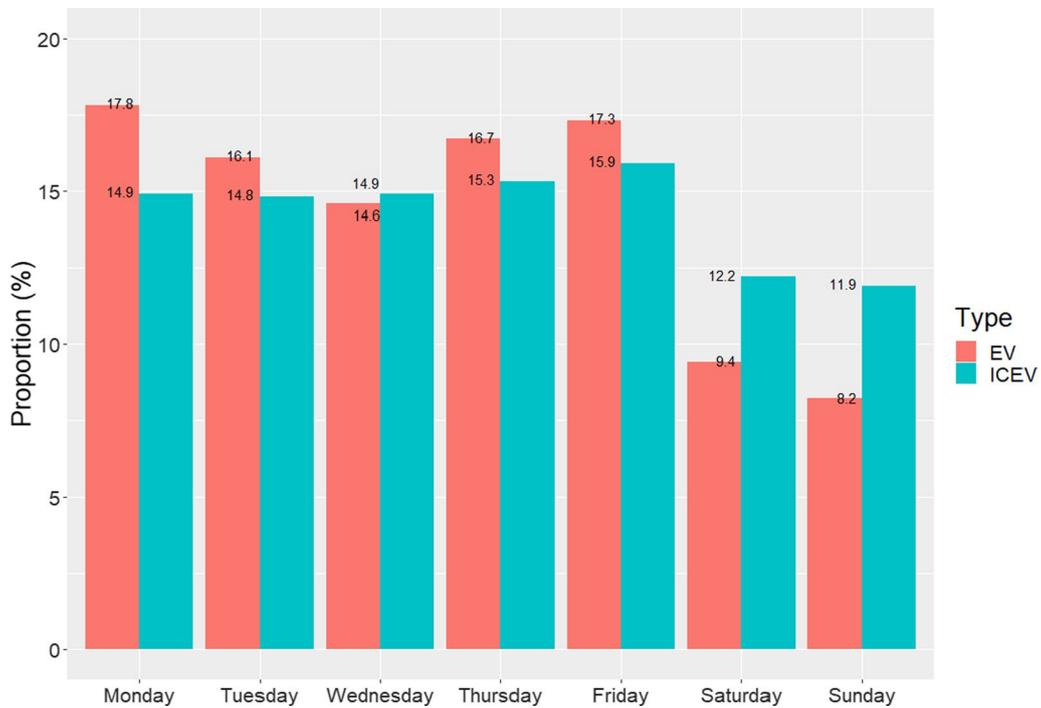


**Fig. 3** Distributions of crashes by day of week
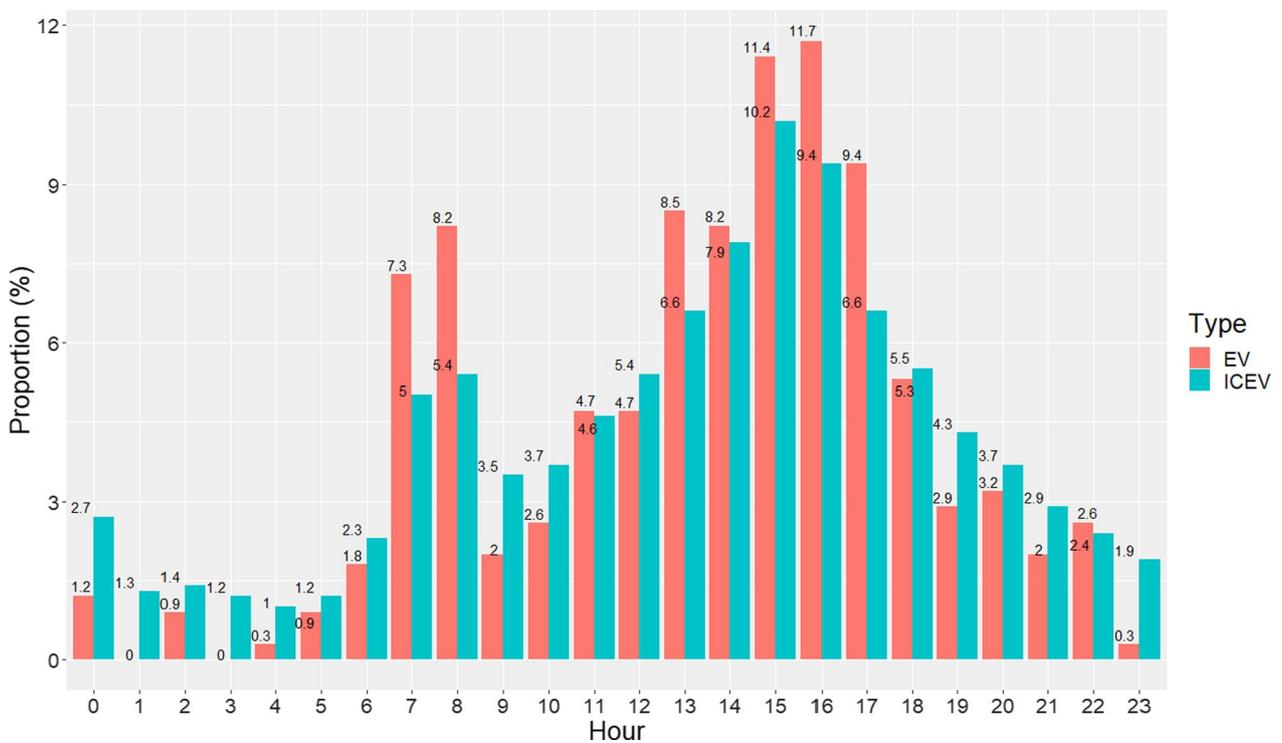


**Fig. 4** Distribution of crashes by time of day

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**Table 2** Distributions of crashes by settlements

| Settlements | ICEV (%) | EV (%) |
|---|---|---|
| Urban areas | 33.4 | 50.9 |
| Rural areas | 55.8 | 37.7 |
| Unknown | 10.8 | 11.4 |

**Table 3** Distributions of crashes by speed limit

| Speed limit (km/h) | ICEV (%) | EV (%) |
|---|---|---|
| < 50 | 13.5 | 20.7 |
| ≥ 50 and < 80 | 53.1 | 59.9 |
| ≥ 80 | 32.5 | 19.3 |
| Unknown | 1.0 | 0.0 |

**Table 4** Distributions of crashes by roadway location

| Roadway location | ICEV (%) | EV (%) |
|---|---|---|
| Segment | 62.9 | 47.1 |
| Junction | 36.4 | 51.8 |
| Unknown | 0.7 | 1.2 |

**Table 5** Distributions of crashes by visibility

| Visibility | ICEV (%) | EV (%) |
|---|---|---|
| Good visibility | 75.6 | 75.4 |
| Good visibility—rainfall/snowfall | 13.7 | 13.7 |
| Poor visibility | 5.7 | 5.6 |
| Unknown | 5.0 | 5.3 |

the main roads for long-distance travels, which is a big hurdle for the EV adoption [36].

### 3.3.3 Roadway location
Regarding roadway locations, crashes are divided into two categories: junctions, including cross intersections, roundabouts, exits, bridges, level crossings, tollbooths, etc., and segments, including routes beyond crossings/exits, tunnels, underpasses, etc. As shown in Table 4, 62.9% of ICEV crashes occurred at segments, while this proportion is only 47.1% for EV crashes. That is, EV crashes are more likely to occur at junctions.

### 3.4 Under what conditions do EV crashes occur?
### 3.4.1 Visibility
Different from other factors, distributions of ICEV and EV crashes by visibility are very similar (Table 5). In the dataset, visibility is mainly influenced by weather

**Table 6** Distributions of crashes by roadway surface conditions

| Road surface conditions | ICEV (%) | EV (%) |
|---|---|---|
| Dry | 54.6 | 56.4 |
| Wet | 23.5 | 29.5 |
| Snowy/Icy | 14.7 | 7.6 |
| Unknown | 7.2 | 6.4 |

**Table 7** Distributions of crashes by accident category

| Accident category | ICEV (%) | EV (%) |
|---|---|---|
| Car | 63.8 | 57.9 |
| Motorcycle | 16.0 | 10.5 |
| Bike | 9.9 | 13.7 |
| Pedestrian | 10.4 | 17.8 |

conditions. Three fourths of crashes occurred in good visibility, whereas only 5.6% of crashes occurred in poor visibility.

### 3.4.2 Roadway surface conditions
As a Nordic country, Norway has very long and dark winters with severe snows. Table 6 shows distributions of crashes by roadway surface conditions. It can be found that 14.8% of ICEV crashes occurred on snowy/icy roads, whereas this proportion is only 7.6% for EVs. That is, the probability of EV crashes occurring in icy roads is only about half of that of ICEV ones. It implies that EVs might be less used in inclement weather, probably due to their battery issues.

### 3.5 What are the EV crash partners?
Crashes are divided into four types by accident category in Norway: car, motorcycle, bike, and pedestrian. Table 7 indicates that 31.5% of EV crashes involve bikes/pedestrians, but this proportion is only 20.3% for ICEV ones. It confirms the threat of EVs to pedestrians and cyclists. Meanwhile, 10.5% of EV crashes involve motorcycles, while this proportion is 16.0% for ICEV ones. That is, EVs were less likely to collide with motorcycles.

## 4 Regression analysis on crash severity
Identification of important factors that affect crash severity is essential to formulate appropriate countermeasures. In this section, two logistic regression models are established to determine the statistically significant factors that affect crash severity (i.e., light vs severe) for ICEVs and EVs, respectively.

Table 8 lists a summary of variables used in regression analysis to crash severity. Some variables are

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**Table 8** A summary of variables used for regression analysis to crash severity

| Variable | Definition | ICEV (%) | EV (%) |
|---|---|---|---|
| *Dependent* | | | |
| Severity | 0 if light crash | 84.7 | 86.7 |
| | 1 if severe crash | 15.3 | 13.3 |
| *Independent* | | | |
| Weekend | 0 if it occurred on weekdays[a] | 76.1 | 82.4 |
| | 1 if it occurred on weekends | 23.9 | 17.6 |
| Time of day | AM peak (7–8 a.m.) | 10.2 | 16.2 |
| | Daytime (9 a.m.–2 p.m.)[a] | 32.4 | 29.1 |
| | PM peak (3–5 p.m.) | 26.4 | 31.7 |
| | Nighttime (6 p.m.–6 a.m.) | 31.1 | 23.0 |
| Settlements | Urban area[a] | 37.3 | 56.1 |
| | Rural area | 62.7 | 43.9 |
| Speed limit | Low-speed (< 50 km/h) | 13.7 | 21.6 |
| | Middle-speed (≥ 50 and < 80 km/h)[a] | 52.9 | 59.4 |
| | High-speed (≥ 80 km/h) | 33.4 | 19.1 |
| Roadway location | Segment[a] | 63.4 | 44.6 |
| | Junction | 36.6 | 55.4 |
| Presence of medians | No[a] | 89.5 | 82.4 |
| | Yes | 10.5 | 17.6 |
| Visibility | Good visibility[a] | 79.8 | 78.4 |
| | Good visibility—rainfall/snowfall | 14.3 | 15.1 |
| | Poor visibility | 5.9 | 6.5 |
| Road surface conditions | Dry[a] | 59.3 | 58.6 |
| | Wet | 25.1 | 32.4 |
| | Snowy/icy | 15.6 | 9.0 |
| Accident category | Car[a] | 64.0 | 55.8 |
| | Motorcycle | 16.2 | 11.5 |
| | Bike/pedestrian | 19.8 | 32.7 |

[a] Indicates the baseline of the variable

recategorized to balance sample sizes in each category without losing the representativeness. Only crashes with definite values for these variables are adopted here. Out of the total 35,441 ICEV and 342 EV crashes, 28,442 and 278 of them are kept in the following regression analysis, occupying 80.2% and 81.3% of the raw data, respectively.

The explanatory variables mainly include time factors (day of week, time of day), location factors (settlements, speed limit, roadway location, and the presence of median), environmental factors (visibility and road surface conditions), and crash partner factors (accident category). Based on the findings in the last section, many variables are redefined. For time indicators, day of week is reclassified into weekday and weekend to reflect distributions of crashes on weekdays and weekends; time of day is reclassified into four types: AM peak (7–8 a.m.), daytime (9 a.m.–2 p.m.), PM peak (3–5 p.m.), and nighttime (6 p.m.–6 a.m.), to reflect distributions of crashes

over hours; for accident category, bike and pedestrians are merged as non-motorized objects.

The estimated results of logistic regression analysis to crash severity for ICEVs and EVs are shown in Table 9. Overall, the results show that most explanatory variables are statistically significant for ICEV crashes, but not for EV crashes. Interpretations of the model results are detailed below.

### 4.1 Time factors
Weekend shows the significantly positive effect for ICEV crashes but is statistically insignificant for EV crashes. That is, ICEV crashes on weekends are generally more severe than those on weekdays. The possible explanation is that ICEV crashes might mainly occur in the short-distance low-speed commuting travels on weekdays, but in the long-distance high-speed discretionary travels on weekends. However, due to the range limitation, EVs are used few in long-distance travels [36]. Therefore, no

**Table 9** Estimated results of logistic regression analysis to crash severity for ICEVs and EVs

| Variable | ICEV | | EV | |
|---|---|---|---|---|
| | Coefficient | 95% CI | Coefficient | 95% CI |
| (Intercept) | − 2.232 | (− 2.346, − 2.119)[a] | − 1.427 | (− 2.632, − 0.330)[a] |
| Weekend | 0.168 | (0.092, 0.244)[a] | 0.340 | (− 0.600, 1.215) |
| Time of day—AM peak | − 0.111 | (− 0.236, 0.012) | − 1.040 | (− 2.626, 0.248) |
| Time of day—PM peak | − 0.180 | (− 0.271, − 0.091)[a] | − 0.431 | (− 1.351, 0.468) |
| Time of day—nighttime | 0.150 | (0.068, 0.232)[a] | − 0.637 | (− 1.729, 0.371) |
| Rural area | 0.249 | (0.153, 0.346)[a] | − 0.215 | (− 1.390, 0.927) |
| Speed limit—low | − 0.249 | (− 0.363, − 0.136)[a] | − 0.636 | (− 1.715, 0.349) |
| Speed limit—high | 0.456 | (0.371, 0.542)[a] | 0.264 | (− 0.940, 1.467) |
| Junction | − 0.428 | (− 0.507, − 0.349)[a] | − 0.589 | (− 1.415, 0.226) |
| Presence of medians | − 0.608 | (− 0.738, − 0.482)[a] | − 1.424 | (− 3.304, − 0.108)[a] |
| Good visibility—rainfall/snowfall | − 0.148 | (− 0.268, − 0.028)[a] | − 0.704 | (− 2.400, 0.785) |
| Poor visibility | − 0.161 | (− 0.317, − 0.008)[a] | 0.722 | (− 0.816, 2.164) |
| Road surface conditions—wet | 0.005 | (− 0.094, 0.102) | 0.055 | (− 1.098, 1.105) |
| Road surface conditions—snowy/icy | − 0.064 | (− 0.174, 0.044) | 0.190 | (− 1.248, 1.424) |
| Accident category—motorcycle | 0.860 | (0.770, 0.950)[a] | 1.345 | (0.249, 2.409)[a] |
| Accident category—bike/pedestrian | 1.152 | (1.054, 1.251)[a] | 0.848 | (− 0.152, 1.910) |

*CI* confidence interval

[a] Indicates significance at alpha = 0.05 level

matter on weekdays or weekends, EVs are mainly used for short-distance local travels. Thus, EV crashes might not show statistically significant differences in severity by day of week.

Besides, AM peak, PM peak, and nighttime show statistically insignificant, significantly negative, and significantly positive effects on the severity of ICEV crashes, respectively. It is thought that congestions at PM peaks might deter the occurrence of high-speed collisions, while nighttime driving often accompanies with fatigue, impaired drivers, speeding, and so on. However, none of them show significant effects on the severity of EV crashes. As shown above, EVs are mainly used at rush hours. This finding implies that at PM peaks, travel patterns of EVs might be different from ICEVs.

### 4.2 Location factors
Settlements show significantly positive effects on the severity of ICEV crashes. That is, ICEV crashes are more severe in rural areas, probably because vehicles travel faster on rural roadways.

The low-and high-speed limit indicators show significantly negative and positive effects on ICEV crashes, respectively. That is, compared to middle-speed roadways, ICEV crashes are less severe on low-speed roadways but more severe on high-speed roadways. It is reasonable as crash severity is expected to increase with the increase of speed [37].

Meanwhile, the junction coefficient is significantly negative for ICEV crashes. That is, crashes occurring at segments are more severe than those at junctions. A possible explanation is that at junctions, such as exits, roundabouts, intersections, vehicles might be more likely to run at low speeds. None of these indicators are statistically significant for EV crashes.

The presence of medians shows significantly negative effects on the severity of both ICEV and EV crashes. That is, crashes occurring on roadways with medians are generally less severe, probably because medians prevent vehicles running into the opposite direction to avoid severe head-on crashes. Further exploration indicates that for ICEVs, proportions of head-on crashes in total crashes occurring at roadways with and without medians are 1.5% and 14.9%, respectively; for EVs, proportions of head-on crashes in total crashes occurring at roadways with and without medians are 2.2% and 10.0%, respectively. Both confirm that the presence of medians did greatly reduce head-on collisions.

### 4.3 Environmental factors
Norway is famous of the long dark winters with big snows. In terms of visibility, good visibility with snowfalls/rainfalls and poor visibility show significantly negative effects for ICEV crashes. That is, compared to good visibility conditions, ICEV crashes in poor visibility or good visibility with snowfalls/rainfalls conditions are less

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severe. It is probably because drivers drive more slowly and carefully in these conditions [38].

Similarly, in terms of road surface conditions, neither indicator is statistically insignificant for ICEV crashes. That is, crashes occurring at wet roads and snowy/icy roads do not show statistically significant differences from those at dry roads in severity for ICEVs. A possible explanation is that people might drive more carefully on these roads, which offsets the impact of slippery pavements. The finding can also be kind of confirmed by the fact that only 15.6% of ICEV crashes occurred on snowy/icy roads, although winters usually last more than 6 months (Oct to April) in Norway. None of these indicators is statistically significant for EV crashes, probably because EVs are mainly used for urban low-speed commuting travels. The relative smooth operating environments reduce the impacts of adverse environmental factors on the severity of EV crashes.

### 4.4 Crash partner factors
For ICEV crashes, both motorcycle and bike/pedestrian indicators show significantly positive effects. In other words, crashes between ICEVs and motorcycles/bikes/pedestrians are more severe than those between ICEVs and passenger cars. This should be because motorcyclists, bicyclists, and pedestrians are vulnerable in crashes. However, for EV crashes, only the motorcycle coefficient is significantly positive, whereas the bike/pedestrian coefficient is statistically insignificant. Although EVs are much more likely to collide with pedestrian/bike than ICEVs, collision outcomes seem not necessarily to be bad. It might still be attributed to the low-speed local travel-dominated travel patterns of EVs.

### 5 Conclusion and discussion
In the context of advancing to the sustainable mobility, the energy-saving and emission-reducing EVs have gained huge growths in the past decades. However, meanwhile, their unique design, manufacturing, and usage characteristics also bring many new challenges to traffic safety. Although many studies have explored safety performance of EVs from various aspects, few of them have analyzed the real-world EV crash data. With the crash data from 2011 to 2018 in Norway, where EVs have the highest market penetration rate in the auto market globally, this study is designed to get a full picture of the status quo of EV crashes and the focus is to figure out that compared to ICEV crashes, what unique features EV crashes have.

It is found that although EV crashes still only occupy a small part of total traffic crashes, their share had been consistently rising to 3.11% in 2018. In terms of crash severity, EV crashes do not show statistically significant differences from ICEV ones. Overall, EV crashes are more likely to occur in weekday peak hours, urban areas, roadway junctions, low-speed highways, and good visibility conditions. These features are thought to be attributed to their usage patterns: EVs are mainly used for urban short-distance commuting travels due to the limitation of battery range and their high adoption costs. Besides, nearly one third of EV crashes involve cyclists and pedestrians, which is nearly 1.5 times of that of ICEV crashes. The finding confirms the threat of EVs to cyclists/pedestrians. Then, two logistic regression models are built to identify the important factors influencing the severity of ICEV and EV crashes, respectively.

It is found that although many factors show statistically significant effects on the severity of ICEV crashes, only few factors show statistically significant effects on the severity of EV crashes. For EV crashes, the presence of medians could significantly lower the severity, and collisions with motorcycles are significantly more severe than those with cars. Both indicators show similar effects for ICEV crashes. Although the small size of the EV crash dataset might affect the regression results, many findings could still be related to usage patterns and operational properties of EVs. Based on these findings, some specific insights might be considered for transportation agencies in EV safety management as follows.

- EVs are confirmed to be great threats to pedestrians and cyclists. Some studies have proposed adding addition acoustic warning signals to EVs [39–41]. Actually, the European Union (EU) has mandated all new e-cars to be fitted with a new sound-emitting device, i.e. the acoustic vehicle alerting system (AVAS), as of 1 July 2021 [42]. The device will automatically generate a sound from the start of the car up to the speed of approximately 20 km/h, and during reversing. Our findings corroborate the necessity of implementing similar regulations in Norway.
- Some factors exhibit very different effects on ICEV and EV crashes. Further investigations are needed before determining whether these factors-based strategies for preventing ICEV crashes still work for EV crashes. If not, they might be adjusted regarding features of EVs.
- The presence of medians on roadways is found to be able to significantly reduce the severity of EV crashes. It is found that medians greatly reduced head-on collisions. Therefore, installing medians at appropriate roadways is also effective for preventing severe EV crashes.
- EVs are found to be especially dangerous for motorcycles in terms of crash severity. Therefore, special

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attention should be paid to motorcyclist protection in the future EV era.

A major limitation of this study lies in that the EV crash data is still very small comparing to ICEV crashes, although it is already one of the most comprehensive EV crash databases in the world. It is suggested that with the accumulation of EV crash data over time, researchers should conduct such research periodically to get more insights in the future. Researchers might also consider utilizing crash data from other countries to get a big EV crash data pool. Besides, in this study, EVs are consisted of PHEVs and BEVs, which, however, might have some different features [25]. Unfortunately, they are not differentiated in the dataset. Future studies might consider conducting separate analysis to PHEV crashes and BEV crashes to get more refined results when such information is available. Thirdly, driver demographic and socio-economic characteristics are widely thought to be important in crash studies. However, such data is also unavailable in our dataset due to the privacy issue. Future studies might also consider taking these features into account when they are available. Finally, the EV post-crash rescue is often tricky for first responders due to the unique physical and operational features of EVs. Many studies have indicated that the post-crash rescue could greatly impact crash outcomes [43, 44]. Therefore, future studies might also consider taking the post-crash rescue into account in the EV crash severity analysis.

### Authors' contributions
C.L., C.L.: study conception and design; C.L., L.Z.: literature review; C.L.: data collection; C.L.: methodology, analysis, and interpretation of results; C.L., L.Z.: draft manuscript preparation. All authors reviewed the results and approved the final version of the manuscript.

### Decalrations

### Competing interests
The authors report no declarations of interest.

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## Publisher's Note