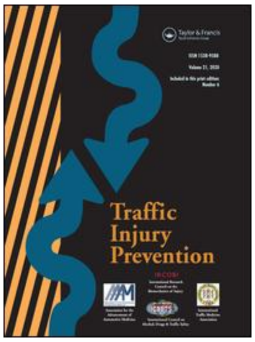

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Impact of adaptive cruise control (ACC) system on fatality and injury reduction in China

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Impact of adaptive cruise control (ACC) system on fatality and injury reduction in China

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ABSTRACT

Objectives: The road traffic safety situation around the world is not optimistic. The development of intelligent vehicles has become an ideal way to reduce road traffic crashes. The adaptive cruise control (ACC) system is an effective intelligent vehicle active safety system for avoiding certain types of collisions. This study aimed to assess the safety benefits of ACC in China, including the potential maximum impact and realistic impact.

Methods: This study applies a national-level safety impact evaluation model to assess the safety benefits of ACC in China, including the potential maximum impact and realistic impact. Road traffic fatality and severe injury trends in China, proportion of different collision types in China, effectiveness of collision avoidance, and market penetration rate of ACC are considered in the potential maximum impact scenario. Furthermore, the ACC activation rate and the technology's technical limitations, including its effectiveness in different weather, light, speed, and road conditions, are discussed in the realistic scenario.

Results: With a 100% market penetration rate, fatalities could be reduced by 5.48%, and injuries could be reduced by 4.91%. With a large increase in market penetration rate of ACC in the coming future, the reductions in fatalities and severe injuries are 324–957 and 1,035–2,737 in 2025 and 531–1,579 and 1,604–4,242 in 2030. Considering ACC's activation rate and its 4 main limitations, the adjusted realistic result is approximately one-third of the potential maximum result.

Conclusions: The result clearly shows that the ACC system can improve road traffic safety in China. Technical limitations have a great impact on ACC's safety benefits. Of all of the limiting factors, the turn-on rate provides the most room for improvement, and improving the suitability of the ACC system on curved and sloped roads provides the smallest effect.

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KEYWORDS
Safety impact; intelligent connected vehicles; adaptive cruise control (ACC); fatality reduction; injury reduction

Introduction

It is reported by World Health Organization (2018) that the number of road traffic deaths reached 1.35 million in 2016, which is the eighth leading cause of death for all age groups, surpassing HIV/AIDS and tuberculosis. In China, there were 63,772 deaths and 209,645 severe injuries in road traffic crashes in 2017. Of these, 6,111 deaths were from rear-end collisions, accounting for 9.58% of all fatalities in road traffic crashes. In addition, 16,409 severe injuries were from rear-end collisions, accounting for 7.83% of all injuries in 2017. Fatalities and injuries resulting from sideswipe collision accounts for 5.01% and 7.39% (The Ministry of Public Security of China 2018).

The adaptive cruise control (ACC) system is considered an effective active safety system for avoiding rear-end and sideswipe collisions. ACC is an advanced assistance system that adjusts vehicle velocity and provides a specified distance to the preceding vehicle by automatically controlling the throttle and/or the brake based on the environmental data available from vehicle sensors (such as radar, lidar, or a camera; Varotto et al. 2020). An ACC-equipped vehicle travels at a user-set velocity when there is no preceding vehicle. An independent evaluation reported that ACC systems would prevent 6% to 15% of all rear-end crashes in the United States each year (Najm et al. 2006). In another project (Deployment of Interurban ATT Test Scenarios (DIATS) 1998), it was reported that the average safety improvement for lane-change collisions and rear-end collisions was 8% and 20%, respectively. In another study, a 45% reduction in fatalities and a 30% reduction in injuries in rear-end collisions was estimated because the frequency of dangerous headways decreases when the ACC function is turned on (Wilmink et al. 2008). In addition, drivers with ACC were inclined to perform 36% fewer lane changes in traffic in a naturalistic driving study (Schakel et al. 2017). Rather than overtaking, participants chose to stay in the slower lane and let ACC follow the predecessor. Additional references can be found in Appendix B (see online supplement).

The total number of collisions that can be reduced by the use of ACC systems in different countries differs due to the proportion of various types of traffic collisions in each country. Based on police-reported crash data in New South Wales (1999–2008), 1,202 fatal crashes and 16,208 injury crashes were

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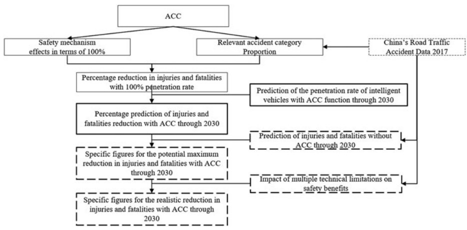

Figure 1. Evaluation model used in this study.

identified, which accounted for 25% of all fatalities and 8% of all injury crashes (Anderson et al. 2010). Using police accident reports for 4 major counties in California and simulations, another study showed that the use of ACC could potentially reduce traffic crashes by up to 7.5% (Yoo 1994). A study in the European Union showed that considering the share of rear-end collisions in all collisions, ACC systems could reduce fatalities and injuries by approximately 2% and 4%, respectively (Wilmink et al. 2008).

A higher reduction in collision risk was achieved as the ACC vehicle penetration rate increased (Li et al. 2017). Considering the market penetration rate is necessary to evaluate the effectiveness of active vehicle safety systems (Jeong and Oh 2017). A penetration rate of 25% could reduce fatalities and injuries by 0.5% and 1.1%, respectively (Wilmink et al. 2008). It was reported that fatal and severe accidents could be significantly reduced by 15% to 33% at a penetration rate of 30% (Zhang and Benz 1993). Additional references can be found in Appendix B.

This article evaluates the safety impacts of ACC systems on fatality and injury reduction in China. The next section describes the research methods and basic data, followed by the number of injuries and fatalities that could be avoided by ACC each year. The impact of multiple technical limitations on safety benefits is analyzed next. The final section provides a discussion and concluding remarks.

Methods

In this study, the number of fatalities and injuries without ACC through 2030 are multiplied by the percentage reduction in fatalities and injuries with ACC through 2030 to obtain specific numbers for the potential maximum reduction in fatalities and injuries with ACC through 2030. Considering technical limitations of ACC including applicable weather, applicable light, and applicable speed, as well as turn-on rate, specific calculations for the realistic reduction in injuries and fatalities are carried out based on the potential maximum reduction, as shown in Figure 1 and Eqs. (1) and (2).

In previous research estimating the safety benefits of advanced technology in intelligent vehicles, some factors of ACC systems such as weather limitation and speed limitation were considered. A Swedish study reported that the lane departure warning system could reduce crashes on roads with speed limits between 70 and 120 km/h and on dry or wet road surfaces (Sternlund et al. 2017). When road surface condition, lighting condition, and speed condition were factored into the estimation, the overall system impact of lane departure warning on crash reduction was reduced to 33% from the unadjusted value of 47% (Gordon et al. 2010). In this study, ACC system limitations such as the proportion of applicable weather conditions, applicable light conditions, applicable road conditions, and applicable speed conditions were considered. This study is a more comprehensive and systematic assessment.

$$SI_{fat,y} = CN_{fat,y} * EC_{fat} * PR_y * PW_{fat} * PL_{fat} * PS_{fat} * PCS_{fat} * PO \quad (1)$$

$$SI_{inj,y} = CN_{inj,y} * EC_{inj} * PR_y * PW_{inj} * PL_{inj} * PS_{inj} * PCS_{inj} * PO \quad (2)$$

where $SI_{fat,y}$ is the specific number of fatalities reduced by ACC in year y; EC_{fat} is the predicted number of fatalities without the ACC system in year y; EC_{fat} is the percentage of fatality reduction when all vehicles are equipped with an ACC system; PR_y is the ACC-equipped vehicle penetration rate for all vehicles in year y; PW_{fat} is the proportion of applicable weather conditions for all fatalities in China; PL_{fat} is the proportion of applicable light conditions for all fatalities in China; PS_{fat} is the proportion of applicable driving speed for all fatalities in China; PCS_{fat} is the proportion of applicable curvature and slope of the road for all fatalities in China; PO is the proportion of driving mileage with ACC enabled in the total mileage; and inj indicates the injury data. Theoretically, factors such as weather condition, light condition, speed distribution could be interrelated. However, these factors are all defined and computed independent of one another in this study because of the lack of more detailed crash data in China.

Penetration rate of ACC in the Chinese market

ACC is a typical system in intelligent vehicles in China, per the classification of intelligent vehicles in China (Ministry of Industry and Information Technology of China 2017). ACC, lane-keeping assist, and automatic parking systems are expected to have different impacts on traffic safety. The calculation in this article only focuses on the safety impact of ACC. The ACC market penetration rate refers to the proportion of intelligent vehicles equipped with ACC out of the total number of vehicles in China, as shown in Eq. (3). Kuang et al. (2019) used a similar idea to predict the fleet penetration of intelligent vehicles. The government's goal is for an annual proportion of new intelligent vehicles in all new vehicles of 50% by 2020, 80% by 2025, and 100% by 2030 (Society of Automotive Engineers of China 2017b). These penetration rates were used in Eq. (3). The Gompertz function in Eq. (4) is widely used to estimate country-level vehicle ownership per 1,000 people based on the ultimate saturation level of vehicle ownership in the country and the gross domestic product (GDP) per capita; Wu et al. 2014). The saturation level of vehicle ownership per 1,000 people in China applied in Eq. (4) is 376, as predicted by the Society of Automotive Engineers of China (2017a). The GDP growth rate in China was predicted to be 4.5% in 2025 and 3.0% in 2030 (Zhang 2017). The population of China was predicted to be 1.4579 billion in 2025 and 1.4643 billion in 2030 (United Nations 2019). The constants ∂ and β in Eq. (4) are −3.3546 and −0.00013, respectively (see Wu et al. 2014). The survival rate of vehicles in China in Eq. (5) was obtained from the Yan and Crookes (2009), which is widely cited.

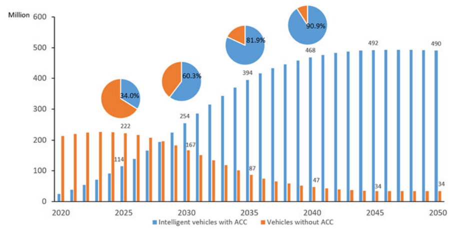

Figure 2. Vehicles with ACC through 2050 in China.

$$PR_y = \frac{\sum_{t=0}^{t=18} NPR_{y-t} * \mathrm{NV}_{\mathrm{y-t}}}{VO_y * Pop_y} \tag{3}$$

$$\mathrm{VO}_y = VOS * \exp\left(\partial \exp\left(\beta PGDP_y\right)\right)/1000 \tag{4}$$

$$\mathrm{NV}_{\mathrm{y}} = \mathrm{VO}_y * Pop_y - \sum_{t=1}^{t=18} SR_t * NV_{y-t}, \tag{5}$$

where $\mathrm{PR_y}$ is the ACC penetration rate in year y; NPR_y is the ACC new vehicle penetration rate in year y; $\mathrm{NV_y}$ is the number of all new vehicles sold in China in year y; VO_y is the number of vehicles owned per capita in year y; Pop_y is the population of China in year y; VOS is the saturation level of vehicle ownership per 1,000 people in China; $PGDP_y$ is the GDP per capita of China in year y; and ∂ and β are 2 constants related to China; SR_t is the survival rate of the year t after the vehicle is sold.

Based on the above, vehicle ownership in China will reach 336 million in 2025 and 421 million in 2030, of which 114 million in 2025 and 254 million in 2030 are intelligent vehicles with ACC systems. The proportion of vehicles equipped with ACC out of total vehicle ownership is calculated to be 34.0% in 2025 and 60.3% in 2030, as shown in Figure 2.

Percentage reduction in injuries and fatalities for ACC with full penetration

Kulmala (2010) developed a comprehensive 9-point mechanisms for the safety assessment of intelligent transport systems that is used to evaluate the percentage reduction in injuries and fatalities for ACC with full penetration. Additional references can be found in the bibliography in Appendix B.

An ACC system adjusts vehicle velocity and provides a specified distance to the preceding vehicle (James et al. 2019). The relevant ACC system safety mechanisms are described as mechanism 1, mechanism 3, and mechanism 8 by Kulmala (2010). Mechanism 1 means direct in-vehicle modification of the driving task. As mentioned in the Introduction, ACC is considered an effective active safety system for avoiding rear-end and sideswipe collisions. ACC has the ability to reduce 45% of fatalities and 30% of injuries in rear-end collisions (Wilmink et al. 2008). ACC can also reduce fatalities and injuries by 36% and 36% in sideswipe collisions due to fewer lane changes (Schakel et al. 2017). Considering the proportion of corresponding collision types in China, the impact of mechanism 1 on total reduction in fatalities and injuries in China is calculated by Eq. (6). In China, fatalities and injuries in rear-end collisions accounted for 9.58% and 7.83% of all fatalities and injuries in 2017, and the proportion of fatalities and injuries in sideswipe collisions is 5.01% and 7.39%, according to the latest Annual Report on Road Traffic Accidents of China (2017). It is assumed that the proportion of different collision types in China will not change in future years.

Mechanism 3 means indirect modification of user behavior. While driving with ACC activated, participants revealed a lower workload level (Vollrath et al. 2011) and drivers are willing to accept shorter following gaps (Nowakowski et al. 2010). Users undertake distracting tasks (calling, surfing the Internet, etc.) more frequently when driving with ACC turned on (Piccinini et al. 2012). Therefore, mechanism 3 will increase fatalities by 0.9% and injuries by 0.5% (Kulmala 2010). Mechanism 8 means modification of route choice. Eighty-nine percent of drivers agreed or strongly agreed that they would be comfortable using ACC in free-flowing traffic on interstates and freeway, which are safer locations (Kidd and Reagan et al. 2019). Mechanism 8 was assumed to reduce fatalities by 0.22% and injuries by 0.39% due to driving on safer roads more often (Wilmink et al. 2008). It should be mentioned that more recent studies on mechanism 3 and mechanism 8 based on experimental data are not available in the literature. Additional references can be found in Appendix B. Considering related mechanisms, the percentage reduction in fatalities with a 100% ACC market penetration rate is calculated by Eq. (7). The injury reduction percentage is similar.

$$\mathrm{EC}_{m1} = \sum_i EC_i * PC_i \tag{6}$$

$$\mathrm{EC_{fat}} = (1 + EC_{m1}) * (1 + EC_{m3}) * (1 + EC_{m8}) - 1, \tag{7}$$

where $\mathrm{EC_{fat}}$ is the fatality reduction percentage for a 100% ACC market penetration rate; $\mathrm{EC_i}$ is the percentage of fatalities reduced by ACC in a type i traffic collision; $\mathrm{PC_i}$ is the proportion of fatalities caused by type i collision in China; $\mathrm{EC_{m1}}$ is an effect factor due to mechanism 1; $\mathrm{EC_{m3}}$ is an effect factor due to mechanism 3; and $\mathrm{EC_{m8}}$ is an effect factor due to mechanism 8.

Based on the framework, the percentage reduction in fatalities is 5.48% when all vehicles are equipped with ACC, and the percentage reduction in injuries is 4.91%.

ACC key safety impact influence factors

Environmental data provided to ACC systems is available from vehicle sensors such as lidar and cameras (James et al. 2019). The Shanghai General Motor Envision 2018, Ford Motor Company Mndeo 2017, FAW-Volkswagen Magotan 2018, Volvo XC60 2019, FAW Hong Qi H5, Geely Lynk & Co 01, and GreatWall Wey VV5 scored 7.2, 9.2, 5.3, 8.5, 7.0, 8.2, and 5.2, respectively, on the ACC test conducted by i-Vista (2019), as shown in Table A1 (see online supplement), which means that ACC products are not reliable and mature enough. Light condition, weather condition, speed range, curvature, slope, and turn-on rate are considered in this section.

First, ACC can work properly only if the environmental information of the sensor is provided as expected. Millimeter-wave radar and cameras cannot recognize the environmental data when driving in poor lighting conditions such as at night without streetlighting and in poor weather conditions such as snow, fog, wind, sandstorm, and so on. Applicable light conditions for current ACC technology are defined as having lights turned on during the day and dusk, dawn, and night with streetlights, and weather conditions applicable for current ACC technology are defined as sunny and cloudy days. Based on the distribution of light conditions and weather conditions in China, as shown in Table A2 (see online supplement), proportions of applicable light conditions for all fatalities and injuries are 75.58% and 85.51%, and proportions of applicable weather conditions are 88.36% and 88.82%. It would be more accurate if only proportions of applicable light conditions and weather conditions for related rear-end and sideswipe collisions were considered instead of all crashes.

Second, ACC has the limitation of applicable speed range. At present, the ACC function often only works at speeds over 30 km/h, as shown in Table A1. This limitation has been discussed in previous research (Anderson et al. 2010; Rakha et al. 2001). The original data on speed in all collisions only contains information on gear for the colliding vehicle, as shown in Table A3 (see online supplement). The vehicle speed is 15 to 35 km/h in second gear (Ministry of Environmental Protection of China 2013). The vehicle speed is higher than 30 km/h at or above the third gear and 1/4 times at the second gear. Gear data for manual and automatic transmissions were often unclear and thus were eliminated when calculating, because the speed distribution in these situations is unknown. Therefore, the proportion of driving speed over 30 km/h for all fatalities and injuries was calculated to be 85.04% and 81.48% by Eqs. (8) and (9).

$$PS_{fat} = \frac{2.26\% * 0.25 + 5.13\% + 5.57\% + 8.67\%}{1 - 19.09\% - 41.02\% - 16.44\%} = 85.04\% \quad (8)$$

$$PS_{inj} = \frac{3.06\% * 0.25 + 6.21\% + 4.83\% + 6.75\%}{1 - 19.09\% - 41.02\% - 16.44\%} = 81.48\%. \quad (9)$$

Third, current ACC technology does not work as expected on roads with excessive curves and slopes. The 15 vehicle models tested in 2019 only scored an average of 7.17 out of 10 (i-Vista 2019; see Table A1). ACC system performance is negatively affected on roads with excessive curves and slopes due to the sensor's limited field of view. The user's manuals of various models remind the user not to use the ACC function on roads with excessive curves and slopes. Applicable curve and slope road conditions for current ACC technology are defined as straight road and road with simple curves and slopes. Based on the distribution of curve and slope road conditions in China, as shown in Table A4 (see online supplement), proportions of applicable curve and slope road conditions for all fatalities and injuries are 90.28% and 92.61%.

The turn-on rate is also a key factor for the safety benefits of ACC. Drivers may not always turn on crash avoidance and driver assistance technologies while driving due to too many unnecessary warnings (Reagan et al. 2019). Drivers may not be comfortable using ACC in certain contexts (e.g., stop-and-go traffic) because the technologies perform poorly (Kidd and Reagan et al. 2019). Sometimes, ACC system undertakes abrupt braking actions when there is a large amount of space in front of the equipped vehicle (Piccinini et al. 2012). The ACC turn-on rate is different in different field operational tests. ACC was on for 25.3% of all miles driven by volunteer drivers during 4 weeks (20,951 miles) in a Range Rover Evoque with ACC (Reagan et al. 2019). In another field operational test hosted by NHTSA, 66 participants drove a total of 163,000 km, with ACC turned on for 44,000 km (Najm et al. 2006). A field operational test was conducted in a group of 108 randomly selected volunteers in the United States (Francher et al. 1998). The result shows that approximately 56,332 km was covered with ACC control actually engaged out of a total of 183,536 km, for a turn-on rate is 30.7%. In China, the turn-on rate is much higher than that in other countries. As of June 30, 2020, ACC equipped on G3 and P7 (intelligent vehicles produced by XPeng Inc.) had been used for 25.1 million km of driving, and the average ACC utilization rate was 66% (Securities and Exchange Commission 2020). Based on the discussion above, the turn-on rate of ACC in China is assumed to be 66.0%. However, the turn-on rate is different in different traffic situation, and the turn-on rate is accounted for only at an aggregate level because of the lack of more detailed data. Additional references can be found in Appendix B.

The use of ACC is limited by light condition, weather condition, speed range, curvature, slope, and turn-on rate. The probability that ACC is in good working condition is 33.8% for all fatalities and 39.8% for all injuries. These values were obtained by multiplying the quantized results of the limitations above. The assessment for each year's reduction in fatalities and injuries is approximately one-third and three-eighths of the potential maximum results, respectively.

Injuries and fatalities without ACC through 2030

Injuries and fatalities caused by road traffic accidents in China during 2018 to 2030 were predicted based on a mature Grey-Markov model and 2008–2017 data from the *Annual Report on Road Traffic Accidents* of the People's Republic of China (Ministry of Public Security of China, 2018). The injury data in this article refer to severe injuries due to the absence of detailed data on minor injuries in China. Additional reference can be found in the bibliography in Appendix B.

In previous work (Tan et al. 2020), traffic fatalities in vehicles without active safety systems like ACC are predicted to be 55,686 in 2020, 51,420 in 2025, and 47,484 in 2030, and the corresponding values for injuries are 188,285, 164,135, and 143,163, respectively. The relative error is 1% for deaths and 1.3% for injuries.

Scenario definition

Based on the above discussion, 3 different scenarios are defined in this research to discuss ACC's potential and realistic safety impact for reducing fatalities and injuries in China through 2030. Scenario 1 is a baseline scenario, representing injuries and fatalities without ACC through 2030. Scenario 2 is an optimistic scenario, indicating the potential maximum reduction in injuries and fatalities. In the optimistic scenario, it is assumed that an advancement in sensor technology enables ACC to work in bad weather and low light and on roads with excessive curve and slope, with all drivers turning on the ACC system and ACC working effectively over the entire speed range. Scenario 3 is a realistic scenario, representing realistic reductions in fatalities and injuries at the current technology level. The realistic

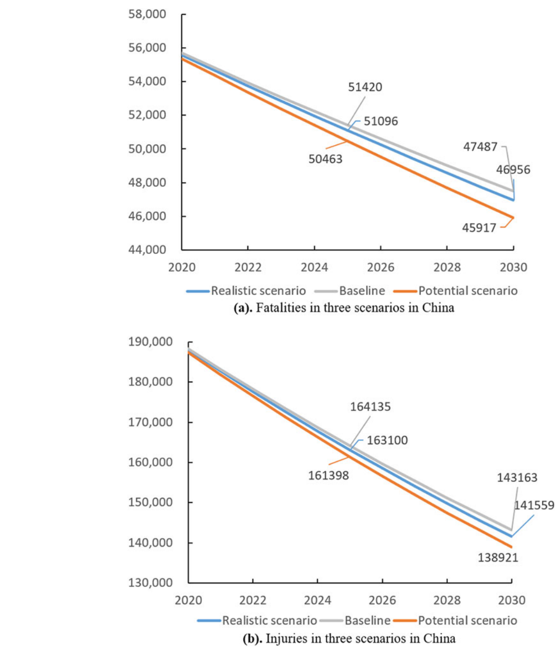

Figure 3. Fatalities and injuries in 3 scenarios in China.

scenario considers the ACC activation rate and its technical limitations, including weather, light, road, and speed conditions.

Results

Based on the predicted number of injuries and fatalities without ACC, the percentage reduction for full penetration, the market penetration rate of ACC each year, and all limitations, the specific reduction in fatalities and injuries with ACC each year in 3 scenarios was calculated, as shown in Figure 3. The potential maximum result is 1,570 fewer fatalities and 4,242 fewer injuries in 2030. In 2025, there will be 957 fewer fatalities and 2,737 fewer injuries. The percentage reduction in fatalities is 5.48% when all vehicles are equipped with ACC, and the percentage reduction in injuries is 4.91%. Even in the optimistic maximum result, ACC will only reduce fatalities and injuries by 3.3% and 2.9% in 2030. The improvement means fewer fatalities and fewer injuries in China, if the government promotes higher market penetration of ACC.

Considering the turn-on rate and other technical limitations including speed, weather, light, and road conditions discussed above, the adjusted realistic result is approximately one-third of the potential maximum result. Based on realistic results, 531 fewer fatalities and 1,604 fewer injuries will occur in 2030. In 2025, there will be 324 fewer fatalities and 1,035 fewer injuries in China. These technical limitations have a significant impact on the safety benefits of ACC. Advances in ACC technology will greatly increase the number of fatalities and injuries that can be avoided.

Discussion

This study applies a national-level safety impact evaluation model to assess the safety benefits of ACC in China, considering the market penetration rate under China's policy plan and historical accident data in China. This is the first study that

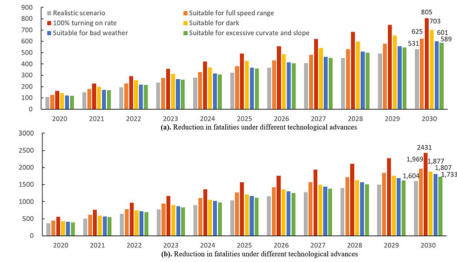

Figure 4. Reduction in fatalities with different technological advances.

provides quantitative insights on safety benefits of ACC in China to guide technology and policy decisions.

The results clearly show that ACC can greatly improve road traffic safety in China. Based on the result of the realistic scenario, one of all limitations was overcome during single-factor analysis. Of all of the limiting factors, the turn-on rate provides the most room for improvement, as shown in Figure 4. Compared to the reduction in the realistic scenario, reduction in fatalities would increase from 531 to 805 in 2030, and the reduction in injuries would increase from 1,604 to 2,431 when all drivers activate the ACC functionality. Compared to the reduction in the realistic scenario, the reduction in fatalities would increase from 531 to 703, and the reduction in injuries would increase from 1,604 to 1,877 if ACC could work effectively in low light conditions. With full speed suitability, the reduction in fatalities would increase from 531 to 625, and the reduction in injuries would increase from 1,604 to 1,969. The reduction in fatalities and injuries would increase to 601 and 1,807 resulting with improved weather suitability. Suitability on curves and slopes has the smallest effect among all the limiting factors, avoiding 57 fatalities and 128 injuries.

Considering ACC's technical limitations, including weather, light, speed, and road conditions and activation rate, a realistic assessment for the yearly reduction in fatalities and injuries is approximately one-third of the potential maximum results. Technical limitations have a great impact on ACC's safety benefits. Of all of the limiting factors, the turn-on rate provides the most room for improvement, followed by light condition, so improvement in the sensor's light detection ability is necessary. Improved effects from improved suitable speed range follow, with improved weather suitability and curves and slopes having the smallest effect. In summary, the best 2 paths to improve the safety benefits of ACC are to improve the turn-on rate and light suitability.

Conflicts of interest

The authors declare no conflict of interest.

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Data availability

All data generated or analyzed during this study are included in this published article and the appendixes. If more detailed data are needed, they are available from the corresponding author.

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