# THE POTENTIAL OF VEHICLE AND ROAD INFRASTRUCTURE INTERVENTIONS IN FATAL PEDESTRIAN AND BICYCLIST ACCIDENTS ON SWEDISH RURAL ROADS – WHAT CAN IN-DEPTH STUDIES TELL US?

**Anders Kullgren**
**Matteo Rizzi**
**Helena Stigson**
**Anders Ydenius**
Folksam Research and Chalmers University of Technology
Sweden

**Johan Strandroth**
Swedish Transport Administration and Chalmers University of Technology
Sweden

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## ABSTRACT

Pedestrian and bicyclist fatalities account for approximately 21% and 8% of all road fatalities in the EU, respectively. The objective was to describe the characteristics of fatal crashes with pedestrians and bicyclists on Swedish rural roads and to investigate the potential of different infrastructure and vehicle interventions to prevent them.

The Swedish Transport Administration (STA) in-depth database of fatal crashes was used to study killed pedestrians (n=75) and bicyclists (n=76) on rural roads during the period 2006-2015. The potentials of several vehicle and infrastructure safety interventions were determined retrospectively for each case by analyzing a chain of events leading to the fatality. The future potential of infrastructure countermeasures was also analyzed based on prognoses on the implementation rate of several vehicle technologies in the Swedish vehicle fleet.

The most common accident scenarios were that the bicyclist was struck while cycling along and at the side of the road; the pedestrian was struck while crossing the road. Most accidents involved a passenger car and occurred on roads with a speed limit of 70 to 90 km/h. The majority of the fatal accidents with bicyclists occurred under daylight conditions (71%), while 62% of the fatal accidents with pedestrians occurred in darkness. Forensic reports suggested that 43% of the non-helmeted bicyclists would have survived with a helmet. It was estimated that a large proportion of the fatal accidents with pedestrians and bicyclists could be addressed by advanced vehicle safety technologies, especially Autonomous Emergency Braking (AEB) and Autonomous Emergency Steering (AES) with pedestrians and bicyclist detection. With regard to interventions in the road infrastructure, separated paths for pedestrians and bicyclists, pedestrian barriers and pedestrian/bicyclist crossings with speed calming measures were found to have the large safety potentials.

However, it was also calculated that it will take a long time until the advanced and potentially effective vehicle safety technologies will be widely spread, which shows the importance of speeding up the implementation rate. A fast introduction of effective interventions in the road infrastructure is also necessary, preferably using a plan for prioritization.

This study had a holistic approach to provide road authorities and vehicle manufacturers with important recommendations for future priorities. However, only accidents on rural roads were included, which means that the findings and conclusions may not apply to urban areas.

## BACKGROUND

According to the political goals of the Swedish transport system, the proportion of bicyclist and pedestrians should increase [1]. However, to be able to see the road transport system as sustainable it must be safe for all road users. This is not the case today, as pedestrians and bicyclists account for approximately 21% and 8% of all road fatalities in the EU, respectively [2]. While similar trends have been reported for Sweden, pedestrians account for the largest proportion of road casualties globally [3]. During the last five years, between 60 and 70 pedestrians and bicyclists were fatally injured in Sweden (excluding suicides), accounting for nearly 25% of all fatalities in the road transport system.

One third occurred on rural roads. The vast majority was struck by a car [4]. The number of fatally injured car occupants has decreased by 60% since the early 2000. During the same period, the number of fatally injured pedestrians and bicyclists has also decreased, although this improvement was concentrated to build-up areas and only marginal on rural roads. Therefore, further initiatives aimed at reducing the number of killed vulnerable road users are needed.

The collision speed of cars is one of the parameters with the highest influence on the risk of fatality and serious injury for vulnerable road users. The fatality risk for pedestrians increases dramatically at collision speeds above 40 km/h [5]. The Vision Zero guidelines recommend a maximum speed limit of 30 km/h when there is a risk for collision with vulnerable road users [6]. But it is possible to adopt further countermeasures. Studies have shown that a combination of speed calming road infrastructure, bicycle helmets and more protective car fronts may reduce the risk for permanent impairment among bicyclists up to 95% [7].

In addition to passive safety systems, Autonomous Emergency Braking (AEB) or Autonomous Emergency Steering (AES) with pedestrian and bicyclist detection have been introduced in cars lately aimed at avoiding or mitigating collisions with vulnerable road users (VRU). Studies have indicated that AEB will reduce the number of injuries among car occupants involved in rear-end crashes [8-10]. Studies have also shown that AEB with pedestrian detection is effective (up to 40% reduction) [11]. However, deeper knowledge is needed regarding the effectiveness of those safety technologies aimed at avoiding or mitigating the severity of collisions with pedestrians and bicyclists, especially on rural roads with higher speed limits and thereby higher demands on the systems. Furthermore, estimations of the effectiveness of existing and coming road infrastructure solutions aimed at targeting vulnerable road users are also needed.

It is important to know to what extent accidents existing today can be prevented in the future to prioritize among different preventive interventions. A relevant and useful method to identify future safety gaps has been used by the Swedish Transport Administration [12, 13].

The objectives of the present paper were to describe the characteristics of fatal crashes with pedestrians and bicyclists on Swedish rural roads and to investigate the potential of different infrastructure and vehicle interventions to prevent them.

## METHODS

The Swedish Transport Administration (STA) in-depth database of fatal crashes was used to study fatally injured pedestrians and bicyclists. Crash investigators at STA systematically inspect the vehicles involved and record direction of impact, vehicular intrusion, seat belt and helmet use, airbag deployment, tire properties, etc. The crash site is also inspected to investigate road characteristics, collision objects, etc. Further information is provided by forensic examinations, witness statements from the police and reports from the emergency services. Collision speeds are generally derived by vehicular deformation, and the initial driving speed is mostly based on eye-witness accounts, brake skids, etc. Pre-crash braking is also coded based on eye-witness accounts, brake and skid marks. The final results of each investigation are normally presented in a report. Because all fatal crashes are included in the sampling criterion, the material can be considered fully representative for Swedish road fatalities.

Due to the low reduction of bicyclist and pedestrian fatalities in rural areas, only accidents on the national road network (mainly rural roads) were included in the present study, accounting for approximately 30% of the total number of fatal accidents with pedestrians and bicyclists in Sweden during the studied accident years, see Table 1. Cases classified as suicides were excluded. In total, 76 killed bicyclists (22 women and 54 men) between 2006 and 2015 and 75 killed pedestrians (27 women and 48 men) between 2011 and 2015 were included, see Table 1. The mean age, stature and weight of the fatally injured pedestrians and bicyclists were 52, 173 cm and 77 kg, respectively.

**Table1. Number of fatalities per accident year on the national road network (mainly rural) and total number of fatalities**

| Accident year | n, bicyclists rural (total) | n, pedestrians rural (total) |
|---|---|---|
| 2006 | 7 (27) | - |
| 2007 | 6 (35) | - |
| 2008 | 9 (32) | - |
| 2009 | 7 (21) | - |
| 2010 | 7 (23) | - |
| 2011 | 9 (22) | 15 (54) |
| 2012 | 10 30) | 16 (50) |
| 2013 | 6 (15) | 18 (44) |
| 2014 | 7 (33) | 18 (55) |
| 2015 | 8 (17) | 8 (28) |
| Total | 76 (255) | 75 (231) |

In total, 155 variables were noted for each accident according to a matrix designed specifically for this study, covering general information of the accident, information on the accident scene and surroundings, on the killed pedestrian or bicyclist and the striking vehicle and its driver.

Also, an estimation of the time between the moment the driver noticed the pedestrian or bicyclist and the impact was made, later defined as time-to-collision (TTC).

The potentials of several vehicle and infrastructure safety countermeasures were determined retrospectively for each case by analyzing the entire chain of events leading to the fatality [14]. By using this model it is possible to avoid double counting of potentials (i.e. a fatality cannot be prevented twice with different interventions) and detailed future estimates can be made.

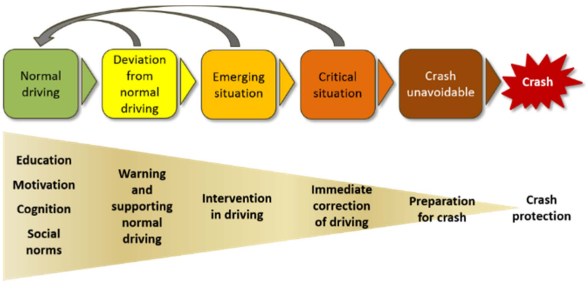


***Figure 1. The chain of events from normal driving to a crash, from [14].***

The relevance of infrastructure countermeasures was analyzed depending on the road width, traffic flow and other road characteristics. Projections were made on future fitment of vehicle technologies shown to be effective. The method is presented by [12, 13] and has previously been used by the Swedish Transport Administration (STA) to manage the national road traffic safety work and to prioritize future interventions.

The analysis was carried out in three separate steps. In the first one, the potentials of different vehicle and infrastructure safety countermeasures were analyzed. In the second step, it was investigated whether each accident would still happen in 2030 or 2050, and if so, whether it would lead to a fatal outcome. Finally, in the third step the fatalities still left in 2030 and 2050 (the so-called residual) were analyzed. Each step is further described below.

1) In the first step the potential of various interventions was made, see list below.

- Separated pedestrian and bicycle paths within the existing road width, for example within the paved road shoulder
- Separated new pedestrian and bicycle paths
- Other road designs such as 2-1 roads (see Figure 2) or shared spaces
- Pedestrian barriers, i.e. fences at highways
- Rumble strips
- Roundabouts
- Pedestrian and bicyclist crossings with speed calming measures (i.e. raised crossings etc.)
- Changed speed limit
- Other speed calming measures, i.e. speed bumps or chicanes forcing the vehicles to reduce speed
- Improved winter road maintenance
- Safe bus stops
- Electronic Stability Control (ESC)
- Antilock brakes (ABS) for two-wheelers (incl. bicycles)
- AEB (Autonomous Emergency Braking) low-speed rear-end (up to 50 km/h)
- AEB with pedestrian and bicyclist detection
- AEB reversing with pedestrian and bicyclist detection
- AEB at intersections
- AEB interurban rear-end
- Lane Departure Warning (LDW) – Lane Keeping Assist (LKA)
- Autonomous Emergency Steering (AES), warns and steers automatically maximum 1 m aside (when there is space) to avoid collisions
- Side radar for HGVs and buses
- Alcohol interlock systems
- Bicycle helmets


***Figure 2. An example of a 2-1 road.***

**Table 2. Future estimates on implementation rates for safety technologies on passenger cars, heavy-good-vehicles and motorcycles, based on [13]**

| Vehicle type | System | Implementation rate | |
|---|---|---|---|
| | | **Fast** Standard MY | **Normal** Standard MY |
| Pass. car | ESC | 2008 | 2008 |
| Pass. car | AEB city | 2020 | 2020 |
| Pass. car | AEB VRU | 2030 | 2030 |
| Pass. car | AEB reverse VRU | 2025 | 2030 |
| Pass. car | AEB inter-section | 2025 | 2030 |
| Pass. car | LDW - LKA | 2025 | 2030 |
| Pass. car | AES | 2025 | 2030 |
| HGV | ESC | 2020 | 2020 |
| HGV | AEB inter-urban | 2016 | 2016 |
| HGV | LDW - LKA | 2016 | 2016 |
| PTW | ABS | 2016 | 2016 |

2) In the second step, an estimate was made of which fatal accidents could be avoided in the future, based on the predicted safety development of the vehicle fleet, see Table 2. For each case, based on the model year of the vehicles involved in the fatal crashes, it was decided whether they would be fitted with a certain safety technology in 2030 or 2050, which would make it possible to avoid the fatality. This kind of prediction has successfully been used by the Swedish Transport Administration to manage the

national road safety work [12, 15, 16]. While these estimations of the development of the vehicle fleet were conservative, it is to date not possible to make estimations for all vehicle safety technologies in the list above (for instance alcohol interlocks).

3) In the last step an analysis of the remaining fatal accidents in 2030 and 2050 was made, i.e. those fatalities not possible to address with expected vehicle safety development (so-called residual). Such approach makes it easier to identify and focus on those accidents that will need further actions in the future.

## RESULTS

The majority of fatally injured pedestrians or bicyclists were struck on the carriageway (76% and 79%, respectively), either when crossing the road (43% and 26%, respectively) or moving on and along the lane (19% and 43%, respectively), see Figure 3. Among bicyclists, the most common accident scenario was when they were struck while cycling on and along the road, while for pedestrians it was crossing the road. Approximately 10% of pedestrians and bicyclists were struck on the paved shoulder. Less than 10% occurred at zebra crossings or bicycle crossings, although none of the analyzed cases included any speed calming measure. Very few accidents occurred on roads with separated lanes.

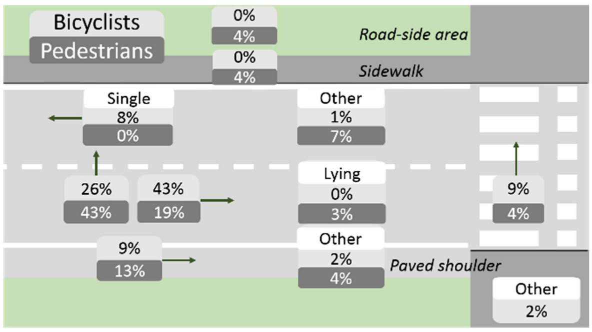


*Figure 3. Description of where the pedestrians and bicyclists were struck.*

The analysis showed that the majority of the pedestrians or the bicyclists were struck by a passenger car (72% and 66% respectively), Table 3. The mean collision speed (including cars, LGV and HGV) was 70 km/h, and frontal impacts were most common.

**Table 3. Distribution of fatalities per vehicle type**

| Striking vehicle | Bicyclists | | Pedestrians | |
|---|---|---|---|---|
| | n | % | n | % |
| Passenger car | 50 | 66 % | 54 | 72 % |
| LGV | 6 | 8 % | 8 | 11 % |
| HGV | 6 | 8 % | 8 | 11 % |
| Bus | 2 | 3 % | 1 | 1 % |
| Other vehicles | 5 | 7 % | 2 | 2 % |
| Single | 6 | 8 % | | |
| Unknown | 1 | 1 % | 2 | 3 % |
| Total | 76 | 100 % | 75 | 100 % |

Nearly 50% of the pedestrians and bicyclists were struck from the side, and 15%-18% from the front, Table 4. A much higher proportion of the bicyclists was struck from the rear (37%) compared to pedestrians (16%).

**Table 4. Distribution of impact directions across fatally injured bicyclists and pedestrians**

| Struck side of VRU | Bicyclists (n=76) | Pedestrians (n=75) |
|---|---|---|
| Front | 15 % | 18 % |
| Side | 43 % | 49 % |
| Rear | 37 % | 16 % |
| Unknown/other | 7 % | 16 % |

Approximately half of the pedestrians or bicyclists had an estimated time-to-collision (TTC) below one second from the moment the driver noticed them, Table 5. TTC below one second was more common among pedestrians (65%), compared to bicyclists (43%). In total 63% had a TTC below two seconds and 73% below three seconds.

**Table 5. Estimated time-to-collision (TTC) from the moment the driver noticed the pedestrian or bicyclist**

| | Number | | | Proportion (%) | | |
|---|---|---|---|---|---|---|
| TTC (s) | Bicy. | Ped. | Total | Bicy. | Ped. | Total |
| 0-1 | 33 | 49 | 82 | 43 | 65 | 54 |
| 1-2 | 8 | 5 | 13 | 11 | 7 | 9 |
| 2-3 | 7 | 8 | 15 | 9 | 11 | 10 |
| 3-4 | 5 | 2 | 7 | 7 | 3 | 5 |
| 4-5 | 2 | 4 | 6 | 3 | 5 | 4 |
| 5+ | 11 | 2 | 13 | 14 | 3 | 9 |
| Unknown | 10 | 5 | 15 | 13 | 7 | 10 |
| Total | 76 | 75 | 151 | 100 | 100 | 100 |

The majority of the fatal accidents with bicyclists occurred under daylight conditions (71%), while 62% of the fatal accidents with pedestrians occurred in darkness, Table 6. An estimation was done of the conditions in which bicyclists or pedestrians were difficult to detect for car sensors: 12% of the bicyclist and 39% of the pedestrian accidents occurred under conditions where a combination of light, weather and/or sight distance (such as heavy rain/snow, fog or blinding sunlight, darkness, etc) could not guarantee a proper detection by the car safety technology. In 12% of the bicycle and 23%

of the pedestrian accidents the vulnerable road user was partly obscured by other vehicles or objects. The majority of the accidents occurred on dry roads (76% for bicyclists and 49% for pedestrians, respectively); 36% occurred on wet roads and 15% on snow or ice.

**Table 6. Lighting condition at the time of accident**

| | Bicyclists | Pedestrians | Total |
|---|---|---|---|
| Daylight | 54 | 27 | 81 |
| Twilight (dusk/dawn) | 1 | 1 | 2 |
| Darkness | 20 | 47 | 67 |
| Unknown | 1 | | 1 |
| Total | 76 | 75 | 151 |

The present material included 6 single bicycle accidents (involving 5 males and 1 female). Two of the bicyclists were heavily drunk (BAC > 1.0 %), 3 occurred while exercising, and one occurred due to a mechanical fault of the bike. Two of the six bicyclists would probably have survived with a helmet.

The analysis showed that 94% of the fatalities among bicyclists could be avoided with the included interventions for road infrastructure, vehicles, bicycle helmet or a combination of them, see Table 7. The most common fatal injury was to the head (60%); 71% of the killed bicyclist did not use a helmet, and forensic reports suggested that 43% of them would have survived with it. However, in almost all of these cases other interventions would have had a positive effect as well. In only 1% of the accidents the helmet would have been the only relevant intervention. Road infrastructure or vehicle safety technologies could have prevented 68% of the fatalities among bicyclists. In four accidents (5%), it was estimated that none of the included interventions would have been able to save the bicyclist. Two of these were single accidents that occurred downhill on a narrow road where the cyclist had a high velocity, one was struck by a truck from behind and one was struck by a wheel loader.

All fatal accidents with pedestrians could have been avoided with the analyzed interventions in the road infrastructure or with vehicle safety technologies, see Table 7. In 71% of the accidents either of the interventions could have saved the pedestrian. In 20% of the accidents only vehicle safety technologies would have prevented the fatality (compared with 3% for bicyclists).

**Table 7. Overview of possible interventions to avoid the fatalities for bicyclists and pedestrians**

| | Pedestrians (n=75) | Bicyclists (n=76) | |
|---|---|---|---|
| | | Survived with helmet | Used helmet/not survived with helmet |
| Road alone | 9 % | 5 % | 13 % |
| Road or vehicle | 71% | 21 % | 47 % |
| Vehicle alone | 20 % | 4 % | 3 % |
| No intervention | 0 % | 1 % | 5 % |
| Total | 100 % | 32 % | 68 % |

The analysis showed that 55% of the bicyclists could be saved by the expected development of the vehicle fleet. However, the maximum benefit would be far ahead in the future (approximately in 2050) due to the predicted implementation rate, see Figure 4. By 2020, 96% of the original accident population would not be addressed and by 2030 between 86% and 95% would be left depending on the implementation rate. A faster implementation rate, shown in Table 2, would mean additional 18 saved lives during a 25-year period compared with the expected normal implementation rate.

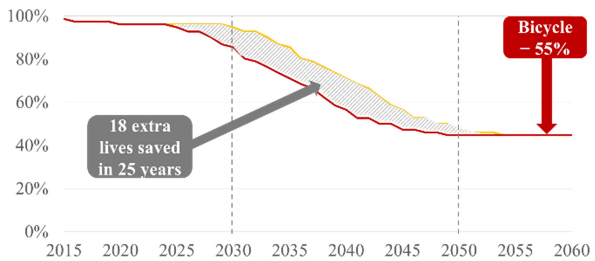


***Figure 4. Future estimate of the development of fatally injured bicyclists due to the implementation of vehicle safety technologies listed in Table 2. Red line = fast implementation rate; yellow line = normal implementation rate.***

The results for pedestrians were similar, up to 53% of the pedestrian fatalities could be avoided with the expected vehicle safety development, see Figure 5. The maximum effect regarding saved lives is expected to be reached in 2050. By 2020, none of the fatalities are expected to be addressed; between 84% and 96% would still remain in 2030. The faster implementation rate would mean additional 21 saved lives in a 30-year period compared to the expected normal implementation rate.

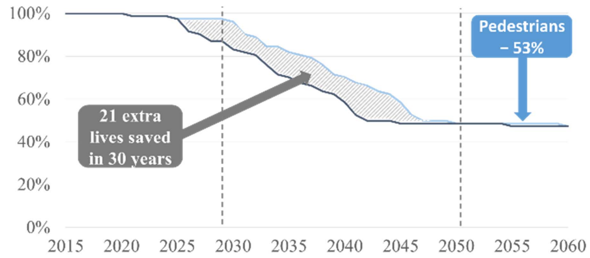


***Figure 5. Future estimate of the development of fatally injured pedestrians due to the implementation of vehicle safety technologies listed in Table 2. Grey line = fast implementation rate; blue line = normal implementation rate.***

In summary, the analysis showed that the overall potential of saved lives (without double counting) was 55% for bicyclists and 53% of for pedestrians. It was estimated that the vehicle safety technologies with the highest potential were AEB and AES for passenger cars with pedestrian and bicyclist detection, between 36% and 43% for AEB and approximately 37%-46% for AES. In further 3%-9% of cases a combination with AEB could have been effective.

The analysis also included a number of other vehicle safety technologies. These were expected to be relevant but no previsions of their implementation rate could be made, for example AEB and AES with VRU detection for LGVs, HGVs and buses, and LDW/LKA for LGVs and buses, side radar for buses and HGVs and alcohol interlock systems for passenger cars and LGVs. The total effect of these additional interventions was 16-20% for bicyclists and 27-33 % for pedestrians. These potentials can be added to the sum in Table 8 (without risk for double counting, since these technologies address a different portion of the accidents).

**Table 8. Potential of safety technologies with an expected implementation rate listed in Table 2**

| Vehicle type | System | Bicyclists | Pedestrians |
|---|---|---|---|
| Pass. car | AES | 46 % | 37 % |
| Pass. car | AEB VRU | 43 % | 36 % |
| Pass. car | AEB VRU+AES | 3 % | 9 % |
| Pass. car | ESC | 3 % | 3 % |
| Pass. car | AEB low speed | 3 % | |
| Pass. car | LKA | 1 % | 1 % |
| Pass. car | AEB intersection | 1 % | |
| Pass. car | AEB reverse VRU | | 1 % |
| HGV | ESC | | 1 % |
| Motorcycle | ABS | | 1 % |
| **Total without double counting** | | **55 %** | **53 %** |

The future estimates made in step 3 showed that the potentials of various interventions of the road infrastructure on fatally injured bicyclists were relatively stable over time, see Table 9. Note that the percentage potential of each intervention relates to an accident population that is decreasing in the future (see Figure 4 and 5). For example, separate pedestrian and bicycle paths outside the carriageway were estimate to have the potential to prevent approximately 50% of the fatalities that occurred 2006-2015 as well as those expected to occur in 2050. However, the number of saved lives in 2050 is expected to be half of the number of saved lives in 2015 because many lives would have already been saved with vehicle safety technologies. The intervention with the highest potential for bicyclists was to build separate paths for pedestrians and bicyclists (approximately 50%), followed by speed calmed crossings with a potential of 22%-25% up to 2030, and then dropping to 16% due to the effect of the implementation of AEB with pedestrian and bicyclist detection. Approximately half of that potential was due to new built crossings (i.e. there was no crossing at all at the time of the accidents). To build a separate lane for pedestrians and bicyclists at the side of the carriageway/lane was estimated to have low potential due to the fact that very few accidents occurred on roads with enough width to build such paths. Similarly, the potentials for roads designed with shared spaces and for safe bus stops were estimated to be low. However, it is important to note that most accidents occurred in rural areas. Therefore these findings may not apply to urban areas.

Overall, the results for pedestrians were similar, see Table 10. The potentials of interventions of the road infrastructure were relatively stable over time. The largest potential was found for separated paths for pedestrians, approximately 30% during the period 2006-2015 and similar in 2050. Pedestrian and bicycle crossings with speed calming measures were also found to have a high potential (approximately 20% up to 2030 and reduced to 7%-9% in 2050 due to implementation of AEB with pedestrian detection). Compared with bicycle accidents, the potential for pedestrians was based on new pedestrian crossings for almost all accidents. In 2050 the potential of pedestrian barriers was estimated to be the second highest (18%). The potential of building separate paths for pedestrians at the side of the carriageway/lane was estimated to have a constant potential of 5%-7%. The potentials of roads designed with shared spaces and for safe bus stops were estimated to be low.

**Table 9. Potential of different road infrastructure interventions for bicyclists in 2006-2015, 2030 and 2050**

| Bicyclists | 2006-2015 (min-max) | | 2030 (min-max) | | 2050 (min-max) | |
|---|---|---|---|---|---|---|
| Separate path for VRUs outside the road | 49 % | 53 % | 49 % | 53 % | 47 % | 50 % |
| Tunnel or bridge | 11 % | 11 % | 11 % | 11 % | 8 % | 8 % |
| Barrier for pedestrians | 1 % | 1 % | 1 % | 1 % | 3 % | 3 % |
| Crash barrier | 0 % | 0 % | 0 % | 0 % | 0 % | 0 % |
| Roundabout | 13 % | 13 % | 14 % | 14 % | 8 % | 8 % |
| Path for VRU on existing road | 1 % | 3 % | 1 % | 3 % | 3 % | 5 % |
| 2-1 road | 11 % | 14 % | 10 % | 13 % | 8 % | 11 % |
| Shared spaces | 1 % | 1 % | 1 % | 1 % | 3 % | 3 % |
| Safe bus stop | 1 % | 1 % | 1 % | 1 % | 3 % | 3 % |
| Rumble strip | 1 % | 4 % | 1 % | 4 % | 0 % | 5 % |
| Pedestrian and bicyclist crossing with speed calming measures | 22 % | 25 % | 22 % | 25 % | 16 % | 16 % |
| *Newly built crossing* | *12 %* | *13 %* | *13 %* | *14 %* | *8 %* | *8 %* |
| Other speed calming measure | 13 % | 13 % | 14 % | 14 % | 11 % | 11 % |
| Changed speed limit | 13 % | 16 % | 14 % | 17 % | 13 % | 18 % |
| Winter road maintenance | 4 % | 4 % | 4 % | 4 % | 3 % | 3 % |
| Other interventions | 7 % | 8 % | 7 % | 8 % | 11 % | 13 % |
| **Total without double counting** | **82 %** | **87 %** | **82 %** | **86 %** | **76 %** | **82 %** |
| Fatally injured bicyclists per year | 7,6 | | 7,2 | | 3,8 | |

**Table 10. Potential of different road infrastructure interventions for pedestrians in 2006-2015, 2030 and 2050**

| Pedestrians | 2011-2015 (min-max) | | 2030 (min-max) | | 2050 (min-max) | |
|---|---|---|---|---|---|---|
| Separate path for VRUs outside the road | 28 % | 33 % | 27 % | 33 % | 29 % | 33 % |
| Tunnel or bridge | 9 % | 9 % | 10 % | 10 % | 11 % | 11 % |
| Barrier for pedestrians | 13 % | 13 % | 14 % | 14 % | 18 % | 18 % |
| Crash barrier | 4 % | 4 % | 4 % | 4 % | 7 % | 7 % |
| Roundabout | 8 % | 9 % | 8 % | 10 % | 7 % | 9 % |
| Path for VRU on existing road | 5 % | 7 % | 5 % | 7 % | 4 % | 7 % |
| 2-1 road | 4 % | 5 % | 4 % | 4 % | 2 % | 2 % |
| Shared spaces | 0 % | 0 % | 0 % | 0 % | 0 % | 0 % |
| Safe bus stop | 1 % | 1 % | 1 % | 1 % | 2 % | 2 % |
| Rumble strip | 4 % | 7 % | 4 % | 7 % | 7 % | 11 % |
| Pedestrian and bicyclist crossing with speed calming measures | 17 % | 20 % | 18 % | 21 % | 7 % | 9 % |
| *Newly built crossing* | *15 %* | *17 %* | *15 %* | *18 %* | *7 %* | *9 %* |
| Other speed calming measure | 13 % | 15 % | 14 % | 15 % | 9 % | 9 % |
| Changed speed limit | 15 % | 16 % | 14 % | 15 % | 7 % | 7 % |
| Winter road maintenance | 1 % | 1 % | 1 % | 1 % | 0 % | 0 % |
| Other interventions | 4 % | 5 % | 3 % | 4 % | 2 % | 4 % |
| **Total without double counting** | **73 %** | **80 %** | **73 %** | **79 %** | **67 %** | **73 %** |
| Fatally injured pedestrians per year | 15 | | 14,6 | | 9 | |

## DISCUSSION

This study had a holistic approach to provide road authorities and vehicle manufacturers with important recommendations for future priorities.

Most often the vulnerable road user was struck by a passenger car and most often on roads with a speed limit between 70 and 90 km/h. Very few accidents occurred on roads with separated lanes. Studies of fatal accidents with bicyclists occurring in Germany, the Netherlands, France, Italy, the UK and Sweden during 2001 and 2012 have shown that more than 50% of all accidents occurred when the bicyclist crossed the road [17]. The findings in the present study indicated a lower proportion, probably due to the fact that only fatal accidents on rural roads were included. More than 80% of the accidents on the national road network included occurred in rural areas, the remaining accidents in urban areas.

71% of the fatal accidents with bicyclists occurred in daylight, which was well in line with European data showing 65-75% of cases occurring in daylight [17]. In the present study, the vast majority of accidents with pedestrians occurred in darkness (63%), although a European study has shown a lower proportion (approximately 50%) [18].

As the accident sample only included roads of the national road network (mainly rural roads) many accidents occurred on roads with high speed limit, especially regarding bicyclists. However, 17-25% of the accidents occurred on roads with a speed limit between 40 and 60 km/h. In a European study [17] 40-60% of the accidents occurred on roads with a speed limit between 50 and 60 km/h. The proportion of accidents on roads with a speed limit above 60 km/h differs a lot between the European countries, probably depending on differences of the infrastructure.

It was found that approximately half of the pedestrians or bicyclists had an estimated time-to-collision (TTC) below one second from the time the driver detected them. In total 63% had a TTC below two seconds. Uittenbogaard et al. [17] found that 80% of the bicycle crossing accidents involving some view-blocking obstruction had a TTC below 2 s. A study where bicycles were fitted with on-board drive recorders [19] showed that car drivers often had a short of time to plan and overtake the bicyclist. When something unexpected happened, forcing the driver to avoid an imminent collision, the driver had very little time to react, often less than 2 s. The study also showed that the driver often kept too short distance to the bicyclist.

Furthermore, it was shown that the most common accident scenario among killed bicyclists on rural roads was when the bicyclist was struck while cycling along and at the side of the road; Table 4 shows that 43% of the killed bicyclists was struck from the side. One explanation is the presence of cyclists along the roadway who suddenly turn across the lane in front of a vehicle, which could also indicate that the driver often kept too short distance to the bicyclist. The most common accident scenario among killed pedestrians was that the pedestrian was struck while crossing the road.

The findings clearly showed that a too short distance and high speed led to a high risk of a fatal accident. These issues suggest that the demands on safety technologies such as AEB and AES may be high.

The number of fatalities in road traffic accidents is decreasing in Europe, especially regarding car occupants. While the number of fatalities among cyclists does not follow the same trend [2, 20, 21], positive interventions have been introduced in cars lately that may have large benefits. Autonomous Emergency Braking (AEB) including pedestrian and bicyclist detection is one example. Currently, AEB systems aimed at avoiding and mitigating car-to-car and car-to-pedestrian collisions are covered in the Euro NCAP tests. From 2018, Euro NCAP will also include AEB with bicyclist detection in their safety assessments. However, the effect on the fatal accidents expected to occur in Sweden by 2030 would be limited due to the expected implementation rate of such relevant technologies. It is important to speed up the implementation rate, for example by including them in consumer tests like Euro NCAP, but also with national scrapping programs, by including such technologies in purchase policies for fleet purchasers, faster legislative actions or economic incentives such as insurance discounts. Technologies like AEB with pedestrian and bicyclist detection need to be implemented also on LGVs and HGVs. Even though the implementation rate would increase with for example scrapping programs, it would still have marginal effect on the societal economical savings. In total, it was estimated that 39 lives would be saved in a 30 year period with a fast implementation rate compared to the expected one. While the prognoses of implementation rates were considered to be conservative, it is important that these should be reviewed in the future and validated against the actual implementation, in order to adjust the predictions of road fatalities. It should be also noted that such prognoses were made specifically for the Swedish market and therefore may not apply to other regions of the world.

Since many of the fatal accidents occurred in darkness (37%) it is recommended that the vehicle sensors for AEB or AES should be able to detect bicyclists and pedestrians in darkness. Furthermore, many accidents occurred under conditions that may be difficult for the sensors. To be able to avoid these accidents the vehicle sensors need to be able to detect pedestrians and bicyclists also (apart from darkness) in heavy rain, fog, blinding sunlight etc.

To achieve the traffic safety goals in Sweden a number of performance indicators are used and followed over time [21]. Important indicators for vulnerable road users are helmet wearing rates for bicyclists and proportion of safe crossings for pedestrians, bicyclists and mopeds. Forensic reports suggested that 43% of the non-helmeted bicyclists would have survived with a helmet. While in almost all of those cases other interventions would have had a positive effect as well, the present study confirmed that bicycle helmets are effective in reducing fatal head injuries among bicyclists.

In 2015 the proportion of safe crossings for pedestrians, bicyclists and mopeds was estimated to be 25% in built-up areas in Sweden [21]. In the same report it was also concluded that this proportion needs to be improved significantly until 2020 in order to reduce the number of road casualties according to the national goals. In this study it was estimated that safe crossings for pedestrians and bicyclists had the potential to avoid 30% of the fatal accidents.

Separated paths for bicyclists and pedestrians were the intervention with the highest potential to avoid the fatal accidents (50%). However, it may be difficult to build separated paths for bicyclists and pedestrians on the majority of the rural roads within a short time frame. A plan for prioritization is therefore necessary. It is also important to note that the safety potentials shown in the present paper would be achieved only with a systematic implementation of the analyzed countermeasures in the whole road network.

The present findings were based on some limitations and assumptions. While the material used was fully representative for Swedish conditions, in such retrospective studies it may be difficult to take into account the possible behavioral adaption that could follow the implementation of certain countermeasures.

Also, the method used in this study has some advantages and drawbacks. One important advantage is that there is a greater knowledge today of vehicle safety technologies to be introduced in the coming years. There is also a better knowledge of the developments of the road infrastructure. For each in-depth study it was investigated whether the accident would lead to a fatality if it happened in 2030 or 2050. A fatal accident that was estimated to be avoided by 2030 or 2050 was removed from the accident sample for the next step, thus providing a population of future crashes that will need further actions. This may be the biggest advantage of this method, compared to other approaches: the result of the predictions is not just the number of fatalities by a certain year, it is rather an actual crash population that can be further analyzed to identify future safety gaps and test different hypotheses. Furthermore, with that approach it is not possible to save one life more than once, i.e. double counting is avoided. The potentials of various interventions were calculated on the accidents 2006-2015 but also from an accident sample that is dynamic and is reducing in the future due to already ongoing interventions. However, the analysis is limited in the sense that influence of post-crash interventions, such as rescue, hospital care and rehabilitation, on fatality outcomes are not included in the analysis. It is difficult to take such effects into account in this type of analysis. It was assumed that rescue, emergency care and rehabilitation would have the same standard in Sweden during the analysis period.

Another limitation is that the potential of improving car crash safety for pedestrians and bicyclists (such as protective front-end design) was not included in the analysis. There is rather limited knowledge of the effect of improved vehicle front-end design in real-life fatal accidents with pedestrians and bicyclists. However, studies have shown a significant correlation between Euro NCAP pedestrian protection scores and the risk for injury and permanent medical impairment based on real-world crashes [7, 22].

A further limitation of this method is that it may be difficult to take future trends into account. An example could be the steadily increased popularity of e-bikes. While all analyzed bicycle accidents involved traditional bikes, it has been reported that the average speed of e-bikes is higher than traditional ones [23], which means a higher injury risk [24]. That may have some implications regarding how to generalize the results to the current accident situation.

A systematic implementation of the analyzed countermeasures of the whole road network is necessary in order to achieve the safety potentials shown in the present paper. Furthermore a systematic review and analysis of fatal accidents with pedestrians and bicyclists also in urban areas using the same approach would be important to get a complete picture of the problem.

## CONCLUSIONS

The most common accident scenario was that the bicyclist was struck while cycling along and at the side of the road, the pedestrian was struck while crossing the road. Most often the vulnerable road user was struck by a passenger car and most often on roads with a speed limit between 70 and 90 km/h. Very few accidents occurred on roads with separated lanes. Based on forensic reports, it was also found that 43% of the non-helmeted bicyclists would have survived with a helmet.

It was estimated that a large proportion of the fatal accidents with pedestrians and bicyclists could be addressed by advanced vehicle safety technologies, especially AEB and AES with pedestrian and bicyclist detection. With regard to interventions in the road infrastructure, separated paths for pedestrians and bicyclists, pedestrian barriers and pedestrian/bicyclist crossings with speed calming measures were found to have larger safety potentials.

However, it will take a long time until the advanced and potentially effective vehicle safety technologies will be widely spread, which shows the importance of speeding up the implementation rate. A fast introduction of effective interventions of the road infrastructure is also necessary, preferably by using a plan for prioritization.

Due to the relatively large number of fatal accidents occurring in darkness or other adverse conditions (heavy rain, fog etc.) it is recommended that the vehicles sensors should be designed to detect pedestrians and bicyclists under such conditions as well.

It is also important to note that the safety potentials shown in the present paper would be achieved only with a systematic implementation of the analyzed countermeasures in the whole road network.

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