# AUTOMATIC EMERGENCY BRAKING – HOW CAN WE SET THE BAR TO MAXIMIZE SAFETY?

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## ABSTRACT

It is estimated that Automatic Emergency Braking (AEB) systems could potentially help mitigate 80% of rear end and pedestrian/cyclist crashes assuming they can stop the vehicle under all circumstances. In practice, however, technical limitations of systems (sensors, control unit, and actuators), vehicle dynamics, and environmental conditions (e.g., lighting, road conditions) reduce the overall crash avoidance performance of AEB systems.

In an effort to better understand these limitations, Transport Canada initiated a study aiming at establishing the general AEB performance of the Canadian vehicle fleet. Three collision scenarios from recognized test protocols were considered: 1) stopped lead vehicle, 2) slower moving lead vehicle, and 3) crossing pedestrian. A total of 43 light duty vehicles (passenger cars, SUVs, and pickup trucks) from 26 different manufacturers were tested for car-to-car scenarios, and 30 vehicles were tested for car-to-pedestrian scenarios. Vehicles' model years ranged from 2013 to 2022. The large sample size of this study covers a significant proportion of the most popular vehicles sold in Canada. To ensure test repeatability, vehicles were equipped with precision positioning systems, audio alert detectors and driving robots. The optimal AEB operating speed range needed to address most real-world collisions was determined from recent crash data. Overall, the performance of vehicles tested was found to improve over the years when compared to the thresholds defined in the U.S. DOT/NHTSA Commitments, but a large proportion struggled to meet the requirements defined in UN regulation No. 152. Interestingly, the results obtained with the best performing systems suggest that it is now possible to achieve even better speed reduction outcomes than the criteria defined in the selected references

The results of this study demonstrate that, with the continuous improvements of AEB systems, it is now possible to exceed performance levels defined in existing requirements. Technological advancements and added capabilities, including pedestrian detection, continue to increase the crash avoidance potential of these systems and, thus, enhance road safety. The methods and criteria evaluated in this study can help to inform future international policy and regulatory requirements.

## INTRODUCTION

Automatic Emergency Braking (AEB) systems are designed to detect potential collisions with obstacles and automatically apply vehicle brakes to avoid or mitigate impacts [1]. A recent study estimated that front-to-rear crashes were reduced by about 50% if the striking vehicles were equipped with AEB compared to those not equipped with the technology [2]. In Canada, this would have corresponded to a reduction of at least 19,600 injuries and 70 fatalities in 2019 alone [3]. Canada has embraced the systems-based approach of Vision Zero [4] with the aim of reducing road fatalities and serious injuries to zero. AEB can be a part of the solution to achieve this goal and the research presented here will help support the development of best practices and the setting of the highest standards, for the cars of tomorrow.

To assess the potential safety benefits of AEB and to better understand technology limitations, Transport Canada and PMG Technologies have been performing Car-to-Car (C2C) and Car-to-Pedestrian (C2P) evaluations on various types of vehicles available to Canadians [5]. Since 2014, over 11,500 AEB tests have been conducted using performance-based evaluation protocols to assess systems' capabilities in preventing or mitigating collisions.

This study used the data collected over time to establish the overall AEB performance of the Canadian vehicle fleet and the results were compared to the reference criteria defined in the U.S. DOT/NHTSA Commitments [6] and UN regulation No. 152 [7]–[9]. The requirements defined in these documents encourage manufacturers to offer AEB on vehicles with a minimum safety performance. Canada has no AEB regulations or consumer assessment program at this point, so the present study benchmarked AEB performance against test procedures available in similar markets (United States and European Union).

The U.S. DOT/NHTSA Commitments (further referenced as "US AEB") is a voluntary agreement between the U.S. government and industry, where the latter committed to include AEB as standard equipment on 95% of their light-duty vehicles and trucks by 2022 (GVWR≤8,500 lbs) and 2025 (8,500 lbs<GVWR<10,500 lbs), depending on Gross Vehicle Weight Rating (GVWR). The US AEB defines a minimum performance criteria for these systems when tested to the protocol developed by the Insurance Institute for Highway Safety in 2013 [10]. UN Regulation No.152 "Uniform Provisions Concerning the Approval of Motor Vehicles with Regard to the Advanced Emergency Braking System (AEBS) for M1 and N1 Vehicles" (further referenced as "UN R152") specifies test methods and performance requirements for AEB car-to-car and car-to-pedestrian evaluations under the type-approval regulatory regime. Comparison of test results with these well-defined criteria provides information on the overall performance of the Canadian vehicle fleet and a benchmarking of the current state of AEB technology.

It is also essential to consider statistics on the type of crashes that this technology is designed to prevent. Recent data from the Canadian National Collision Database, where a collision speed was reported, suggest that 90% of rear-end fatal collisions occur below 120 km/h, and 90% of fatal pedestrian collisions occur below 100 km/h (Figure 1 and Figure 2). A speed was reported for 10 of the fatalities and 3,189 of the injuries that occurred in rear-end collisions (out of a total of 72 and 22,156 respectively). For casualties in single vehicle collisions involving pedestrians, 86 out of the 214 pedestrian fatalities and 1,883 of the 5,572 pedestrian injuries had a reported speed associated with the corresponding collision. While it is not possible to collect impact speed for all collisions, the trends observed in these figures are assumed to represent the overall speed distributions for the respective crash configurations.
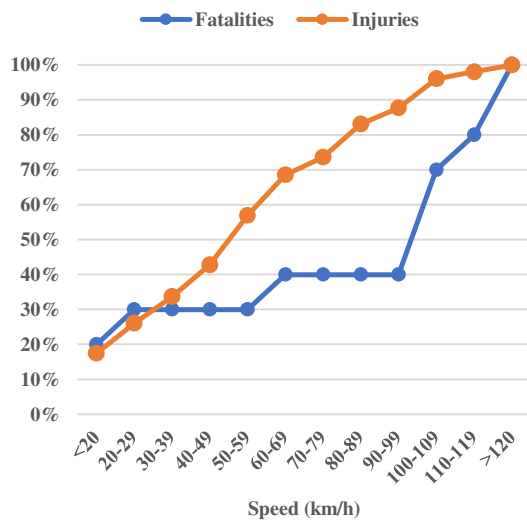


*Figure 1. Cumulative Distribution of Casualties in Rear End Collisions (2020)*
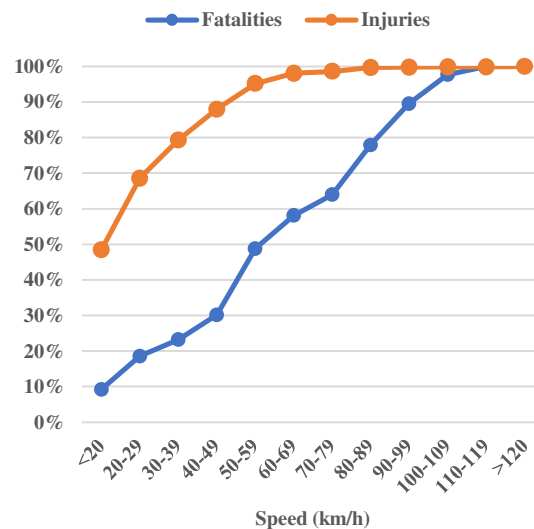
*Figure 2. Cumulative Distribution of Pedestrian Casualties in Single Vehicle Collisions (2020)*

In summary, the aims of this research were to:
1. assess the potential safety benefits of AEB and better understand technology limitations;
2. compare the performance of AEB car-to-car and car-to-pedestrian systems over the years and across vehicles; and
3. identify potential gaps between AEB performance during controlled testing and real-world collisions.

## METHODOLOGY

### AEB Test Protocols and Performance Criteria

This study uses data from tests performed on 54 light duty vehicles (passenger cars, sport utility vehicles, and pickup trucks) from 26 different manufacturers with model years varying from 2013 to 2022. The large sample size covers a significant proportion of the most popular vehicles sold in Canada. The vehicles were evaluated using a subset of scenarios from the following test protocols:
- NHTSA CIB: National Highway Traffic Safety Administration's Crash Imminent Brake System Performance Evaluation for the New Car Assessment Program [11]
- IIHS AEB: Insurance Institute for Highway Safety's Autonomous Emergency Braking Test Protocol [10]
- UN R152: UN Regulation No 152 - Advanced Emergency Braking System for M1 and N1 vehicles [7]–[9]
- Euro NCAP VRU: Euro NCAP AEB VRU Systems Test Protocol valid at the time of testing [12]

The aim of a typical test series was to determine the maximum avoidance speed of a given vehicle by increasing the test speed successively until an impact occurred. An alternative method used for certain test series consisted of performing evaluations at discrete speeds as specified in the relevant test protocols (e.g., UN R152 and C2C B1). The maximum avoidance speed was determined to be the highest speed up to 50 km/h for which a minimum of five avoidances occurred over seven tests, or the equivalent ratio if a different number of tests were performed. For certain scenarios (UN R152), the maximum avoidance speed was found to be the speed at which two tests out of three avoided an impact, or the equivalent ratio. For certain vehicles that performed well at 50 km/h, the speed was increased to further challenge the system under test.

To ensure test repeatability and data accuracy, vehicles were equipped with centimeter-level positioning systems, audio alert detectors and, in most cases, driving robots [5]. Data were verified after each test run to confirm that the tolerances of the test protocols were respected. Figure 3 presents the standardized targets that were used to perform the different test scenarios.



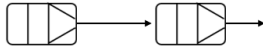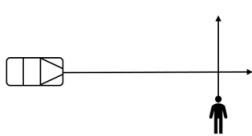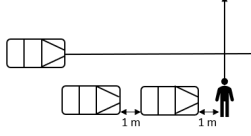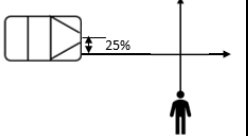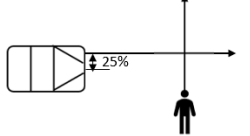| Euro NCAP Vehicle Target (EVT) | Strikeable Surrogate Vehicle (SSV) | Global Vehicle Target (GVT) | Euro NCAP Pedestrian Targets – adult & 7-year-old child (EPTa & EPTc) |

*Figure 3. Test Targets*

The data were analyzed to assess how system performances evolved over the years. Three common test scenarios were considered: 1) stopped lead vehicle [C2C A1], 2) slower moving lead vehicle [C2C B1] and 3) crossing pedestrian [C2P], as described in Table 1 and
Table 2.

*Table 1. AEB Car-to-Car Test Protocols and Scenarios*

| Test Protocol | NHTSA CIB / IIHS AEB (A1 only) / R152 | |
|---|---|---|
| | A1 | B1 |
| Scenario | Stopped Lead Vehicle  | Slower Moving Lead Vehicle  |
| Impact Point | 50% | 50% |
| Target | EVT, SSV and/or GVT | EVT, SSV and/or GVT |

*Table 2. AEB Car-to-Pedestrian Test Protocols and Scenarios*

| Test Protocol | R152 | Euro NCAP VRU | | |
|---|---|---|---|---|
| | Par.6.6 | CPNC-50 | CPNA-25 | CPNA-75 |
| Scenario | Child pedestrian crossing from nearside  | Child pedestrian crossing from nearside with obstruction  | Adult pedestrian crossing from nearside  | Adult pedestrian crossing from nearside  |
| Impact Point | 50% | 50% | 25% | 75% |
| Target | EPTc | EPTc | EPTa | EPTa |

To evaluate the performance of the systems against a common reference, the results for each scenario were compared to the requirements defined in the US AEB and UN R152. Table 3 specifies which criteria was used for the different scenarios and the corresponding pass/fail requirements. Some scenarios were evaluated using both criteria to compare requirements. When necessary, the criteria were adapted for speeds outside of the original requirements, as noted in the table below, and for a reduced number of test runs (i.e., some criteria require five repeated tests at a same speed while for the purposes of this analysis, a smaller number of tests may have been used).

*Table 3. AEB Summary of Requirements*

| Test Scenario | Performance Criteria | Requirement | | |
|---|---|---|---|---|
| C2C (A1) | US AEB* | Option A: *"Average speed reduction across 5 repeated tests that is greater than 10 miles per hour (mph) in either the 12 or 24 mph tests involving a stationary lead vehicle*<br>*OR*<br>Option B: *Average speed reduction across 5 repeated tests that is greater than 5 mph in both the 12 and 24 mph tests involving a stationary lead vehicle."* | | |
| | UN R152 | *Maximum relative impact speed (km/h)* | | |
| | | *Relative speed (km/h)* | *Maximum mass* | *Mass in running order* |
| | | *10* | *0* | *0* |
| | | *15* | *0* | *0* |
| | | *20* | *0* | *0* |
| | | *25* | *0* | *0* |
| | | *30* | *0* | *0* |
| | | *35* | *0* | *0* |

| Test Scenario | Performance Criteria | Requirement | | | |
|---|---|---|---|---|---|
| | | 40 | 0 | 0 | |
| | | 42 | 10 | 0 | |
| | | 45 | 15 | 15 | |
| | | 50 | 25 | 25 | |
| | | 55 | 30 | 30 | |
| | | 60 | 35 | 35 | |
| | | *For relative speeds between the listed values (e.g. 53 km/h), the maximum relative impact speed (i.e. 35/30 km/h) assigned to the next higher relative speed (i.e. 55 km/h) shall apply.* | | | |
| **C2C (B1)** | **UN R152** | *Maximum relative impact speed: 0 km/h* | | | |
| **C2P (all)** | **UN R152** | *Maximum relative impact speed (km/h)* | | | |

Maximum relative impact speed (km/h):

| Relative speed (km/h) | Maximum mass | Mass in running order |
|---|---|---|
| 10 | 0 | 0 |
| 15 | 0 | 0 |
| 20 | 0 | 0 |
| 25 | 0 | 0 |
| 30 | 0 | 0 |
| 35 | 0 | 0 |
| 40 | 0 | 0 |
| 42 | 10 | 0 |
| 45 | 15 | 15 |
| 50 | 25 | 25 |
| 55 | 30 | 30 |
| 60 | 35 | 35 |

*For relative speeds between the listed values (e.g. 53 km/h), the maximum relative impact speed (i.e. 35/30 km/h) assigned to the next higher relative speed (i.e. 55 km/h) shall apply.*

*The same speed reduction requirement was used as a performance criterion for all tested speeds (i.e., speeds below or above 12 and 24 mph)

**Experimental Data Selection and Analysis**

Although specific test protocols are referenced for each performance criteria (i.e., the US AEB references the IIHS AEB test protocol while UN R152 references the R152 test protocol), similar tests performed with a different protocol were selected to increase the sample size. The following assumptions were made during data selection:
- AEB performance is independent from the vehicle target. All test results were grouped together under the same scenario regardless of the vehicle target used (EVT, SSV, or GVT). Evidence from testing has shown that the differences between the vehicles' system responses to different targets are negligible. A comparative study by NHTSA showed that there is negligible effect on the vehicle's response time between the SSV and GVT targets [13]. A similar study conducted earlier between the EVT and SSV targets also concluded that these targets have negligible effect on the response of the vehicles tested [14].
- Scenarios performed as per the Euro NCAP AEB VRU protocol were included in the study to complement the small sample size of UN R152 C2P tests. The same performance criteria were used for all configurations, even if there were several differences between the scenarios (no obstruction vs. obstruction, child vs. adult pedestrian target, 50% impact point vs. 25% and 75%).
- The UN R152 test protocol requires tests to be performed with the vehicle at different masses (mass in running order and maximum mass). Only results from tests performed with the mass in running order were retained for the analysis since it corresponds to the configuration used in the other test protocols evaluated.

Table 4 contains the total number of tests performed per scenario type and model year.

*Table 4. Number of Tests per Vehicle*

| Model Year | Make | Model | Number of tests |
|---|---|---|---|

|  |  |  | C2C | C2P |
|---|---|---|---|---|
| 2013 | Subaru | Legacy | 139 | |
| | Volvo | S60 | 111 | |
| 2014 | Chevrolet | Impala | 58 | |
| | Infiniti | Q50 | 142 | |
| | Jeep | Grand Cherokee | 51 | |
| | Mazda | 6 | 75 | |
| | Mitsubishi | Outlander | 25 | |
| | Subaru | Outback | 95 | |
| | Toyota | Prius | 54 | |
| 2015 | Audi | A3 | 60 | |
| | BMW | i3 | 174 | |
| | Chrysler | 200C | 81 | |
| | Honda | CRV | 71 | |
| | Hyundai | Genesis | 127 | |
| | Mercedes-Benz | C400 | 52 | 28 |
| | Subaru | Impreza | 39 | 26 |
| 2016 | Lincoln | MKX | 76 | 30 |
| 2017 | Ford | Fusion | 57 | 30 |
| | GMC | Acadia | 44 | 33 |
| | Honda | Civic | 59 | |
| | Hyundai | Elantra | 99 | 28 |
| | Kia | Sportage | 64 | 27 |
| | Land Rover | Discovery | 82 | |
| | Mazda | CX-5 | 56 | |
| | Mercedes-Benz | E300 | 55 | 41 |
| | Nissan | Rogue | 32 | 32 |
| | Tesla | Model S | 143 | |
| | Toyota | Corolla | 41 | 29 |
| | Volkswagen | Golf | 75 | |
| | Volvo | XC 90 | 40 | 32 |
| 2018 | Cadillac | CT6 | 56 | |
| | Subaru | Crosstrek | 66 | 26 |
| | Toyota | Prius | | 23 |
| 2019 | Audi | e-tron | 22 | 9 |
| | Hyundai | Santa Fe | 65 | 42 |
| | Nissan | Leaf | | 43 |
| | Tesla | Model 3 | | 26 |
| 2020 | BMW | 330i | 118 | 90 |
| | Buick | Enclave | | 26 |
| | Ford | Explorer | | 33 |
| | Honda | Accord | | 29 |
| | Mazda | 3 | 127 | 71 |
| | Mercedes-Benz | A220 | 87 | 54 |
| 2021 | Alfa Romeo | Stelvio | 14 | |
| | Chevrolet | Silverado | | 45 |
| | Genesis | GV80 | | 52 |
| | Subaru | Ascent | | 51 |
| | Toyota | Camry | 20 | 16 |
| | Volkswagen | Jetta | 19 | |
| | Volvo | XC 60 | | 49 |
| 2022 | Jeep | Grand Cherokee | 20 | 10 |
| | Mitsubishi | Outlander | 9 | |

| Model Year | Make | Model | Number of tests | |
|---|---|---|---|---|
| | | | C2C | C2P |
| | Volkswagen | Taos | 8 | 40 |

For each vehicle, test runs were grouped by scenario and by the relative speed between the vehicle and the target (0 km/h was used in the case of A1 and C2P scenarios). The average relative impact speed was calculated and evaluated per the relevant performance criteria to determine if any result fell outside the requirements. This process was repeated for each scenario and performance criterion. The maximum avoidance speed reached for each scenario was also determined for all vehicles. It should be noted however that many of the tested vehicles may not have been designed to meet the specific test requirements.

## RESULTS

Table 5 presents the results for all vehicles by performance criteria and scenario tested. For a cell highlighted in red, the number indicates the minimum speed at which the result was lower than the evaluated criterion. The green cells indicate that all tests performed by the vehicle met the performance criterion and the maximum speed reached is noted. The table also presents the percentage of vehicles for which all runs met the performance criterion versus the percentage of vehicles for which at least one run did not meet the criterion.

For C2C static target tests (A1), most vehicles met the US AEB criterion, with a larger percentage of vehicles meeting Option A (93%) than Option B (88%). On the other hand, almost two-thirds of the vehicles evaluated had at least one test that fell outside of the UN R152 criterion. In the case of the dynamic target tests (B1), about half of the vehicles met the UN R152 criterion.

When comparing both scenarios performed with the child pedestrian, a larger percentage of vehicles did not meet the UN R152 performance criterion in the occluded scenario (96% for CPNC-50 compared to 43% for Par. 6.6 of UN R152). The 75% impact point scenario with the adult pedestrian (CPNA-75) resulted in a larger percentage of vehicles meeting the requirement (56%) than the scenario with a 25% impact point (37%).

*Table 5. Test Vehicle Performance*

| Model Year | Make | Model | Car-to-Car | | | | Car-to-Pedestrian | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | US AEB | | UN R152 | | UN R152 | | | |
| | | | Option A | Option B | A1 | B1 | Par. 6.6 | CPNC-50 | CPNA-25 | CPNA-75 |
| 2013 | Subaru | Legacy | 55 | 55 | 55 | 40 | | | | |
| 2013 | Volvo | S60 | 40 | 40 | 34 | 30 | | | | |
| 2014 | Mazda | 6 | 20 | 30 | 20 | 10 | | | | |
| 2014 | Mitsubishi | Outlander | 20 | 35 | 20 | | | | | |
| 2014 | Toyota | Prius Plug-In | 20 | 40 | 20 | 24 | | | | |
| 2014 | Subaru | Outback | 70 | 70 | 70 | 40 | | | | |
| 2014 | Jeep | Grand Cherokee | 15 | 15 | 15 | 24 | | | | |
| 2014 | Chevrolet | Impala | 40 | 40 | 30 | 40 | | | | |
| 2014 | Infiniti | Q50 | 50 | 50 | 15 | 24 | | | | |
| 2015 | Mercedes-Benz | C400 | 50 | 50 | 40 | 24 | | 15 | 15 | 50 |
| 2015 | BMW | i3 | 10 | 40 | 10 | 24 | | | | |
| 2015 | Honda | CRV | 50 | 50 | 30 | 40 | | | | |
| 2015 | Audi | A3 | 30 | 30 | 10 | 24 | | | | |
| 2015 | Hyundai | Genesis | 55 | 55 | 20 | 40 | | | | |
| 2015 | Subaru | Impreza | 50 | 50 | 50 | 40 | | 25 | 20 | 50 |
| 2015 | Chrysler | 200 C | 40 | 40 | 25 | 40 | | | | |
| 2016 | Lincoln | MKX | 50 | 50 | 35 | 40 | | 15 | 15 | 15 |
| 2017 | Tesla | Model S | 60 | 60 | 60 | 24 | | | | |
| 2017 | Volvo | XC 90 | 50 | 50 | 50 | 40 | | 40 | 50 | 50 |
| 2017 | Hyundai | Elantra | 50 | 50 | 20 | 24 | | 15 | 15 | 15 |

| Model Year | Make | Model | Car-to-Car | | | | Car-to-Pedestrian | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | US AEB | | UN R152 | | UN R152 | | | |
| | | | Option A | Option B | A1 | B1 | Par. 6.6 | CPNC-50 | CPNA-25 | CPNA-75 |
| 2017 | Mercedes-Benz | E300 | 50 | 50 | 50 | 40 | | 40 | 60 | 60 |
| 2017 | Ford | Fusion | 50 | 50 | 15 | 40 | | 10 | 10 | 20 |
| 2017 | GMC | Acadia | 25 | 30 | 25 | 24 | | 25 | 20 | 35 |
| 2017 | Toyota | Corolla | 50 | 50 | 50 | 40 | | 10 | 10 | 30 |
| 2017 | Nissan | Rogue | 40 | 40 | 35 | 24 | | 20 | 10 | 25 |
| 2017 | Kia | Sportage | 50 | 50 | 35 | 40 | | 30 | 30 | 40 |
| 2017 | Volkswagen | Golf | 45 | 50 | 35 | 24 | | | | |
| 2017 | Land Rover | Discovery | 50 | 50 | 30 | 24 | | | | |
| 2017 | Honda | Civic | 55 | 55 | 20 | 40 | | | | |
| 2017 | Mazda | CX-5 | 50 | 50 | 50 | 40 | | | | |
| 2018 | Toyota | Prius | | | | | | 20 | 20 | 50 |
| 2018 | Subaru | Crosstrek | 50 | 50 | 50 | 40 | | 20 | 50 | 50 |
| 2018 | Cadillac | CT6 | 55 | 55 | 55 | 40 | | | | |
| 2019 | Hyundai | Santa Fe | 60 | 60 | 60 | 40 | | 30 | 40 | 50 |
| 2019 | Nissan | Leaf | | | | | | 40 | 60 | 60 |
| 2019 | Tesla | Model 3 | | | | | | | 50 | 60 |
| 2019 | Audi | e-tron | 70 | 70 | 70 | 40 | 60 | | | |
| 2020 | Ford | Explorer | | | | | | 30 | 45 | 50 |
| 2020 | Honda | Accord | | | | | | | 30 | 25 |
| 2020 | Buick | Enclave | | | | | | 20 | 10 | 45 |
| 2020 | Mercedes-Benz | A220 | 42 | 42 | 20 | 40 | | | | |
| 2020 | BMW | 330i | 42 | 42 | 20 | 40 | 20 | 30 | 60 | 60 |
| 2020 | Mazda | 3 | 60 | 60 | 60 | 40 | 60 | 35 | 30 | 60 |
| 2020 | Mercedes-Benz | A220 | | | | | | 35 | 60 | 60 |
| 2021 | Volvo | XC 60 | | | | | | 40 | 50 | 60 |
| 2021 | Genesis | GV80 | | | | | 55 | 40 | 50 | 60 |
| 2021 | Subaru | Ascent | | | | | | 35 | 60 | 60 |
| 2021 | Volkswagen | Jetta | 50 | 50 | 50 | 40 | | | | |
| 2021 | Alfa Romeo | Stelvio | 50 | 50 | 50 | 40 | | | | |
| 2021 | Chevrolet | Silverado | | | | | | 45 | 20 | 45 |
| 2021 | Toyota | Camry | 70 | 60 | 60 | 40 | 45 | | | |
| 2022 | Volkswagen | Taos | 30 | 30 | 25 | 40 | 40 | 20 | 30 | 40 |
| 2022 | Mitsubishi | Outlander | 40 | 40 | 35 | | | | | |
| 2022 | Jeep | Grand Cherokee | 60 | 60 | 60 | 40 | 45 | | | |
| | | % Pass | 93% | 88% | 37% | 51% | 57% | 4% | 37% | 56% |
| | | % Fail | 7% | 12% | 64% | 49% | 43% | 96% | 63% | 44% |

Next, the maximum avoidance speed reached by each vehicle grouped and averaged by model year and manufacturer was plotted. In order to compare vehicles, the maximum speeds were evaluated up to 50 km/h (indicated by the red line in the graphs below), except for the B1 scenario where the relative speed never exceeded 40 km/h. For the few vehicles evaluated at speeds above 50 k/h, the maximum avoidance speed is indicated on the graph.

The speed reduction in all tests was also calculated for each vehicle and was normalized to the vehicle's test speed. The results were also grouped by model year and by manufacturer. In the case of the C2C B1 scenario (Figure *4*b and Figure *6*b), the speed reduction was capped at the maximum relative speed between the vehicle and target to get a maximum of 1 as a normalized speed reduction. However, certain vehicles braked to speeds lower than the target speed, with some coming to a full stop.

In the following graphs, each bar corresponds to the average value with the minimum and maximum represented by the error bars. The sample size is presented at the bottom of each bar.

The C2C results by model year, as presented in Figure 4, show an evolution in the performance of the vehicles. Apart from 2013, the vehicles progressively reached higher maximum avoidance speeds up to 2019 in the A1 scenario (Figure *4*a). Similarly, the vehicles' normalized speed reduction saw a spike from 2014 to 2016, after which the performance remained above 80% for all subsequent years (Figure *4*c). The maximum avoidance speeds reached in the B1 scenario also increased over the years up to 2018 (Figure *4*b). After 2018, all the vehicles performed full avoidances at all tested speeds, which went up to relative speeds of 40 km/h. The normalized speed reduction also showed that the vehicles were able to reduce the full speed in all tests as of 2018 (Figure *4*d).
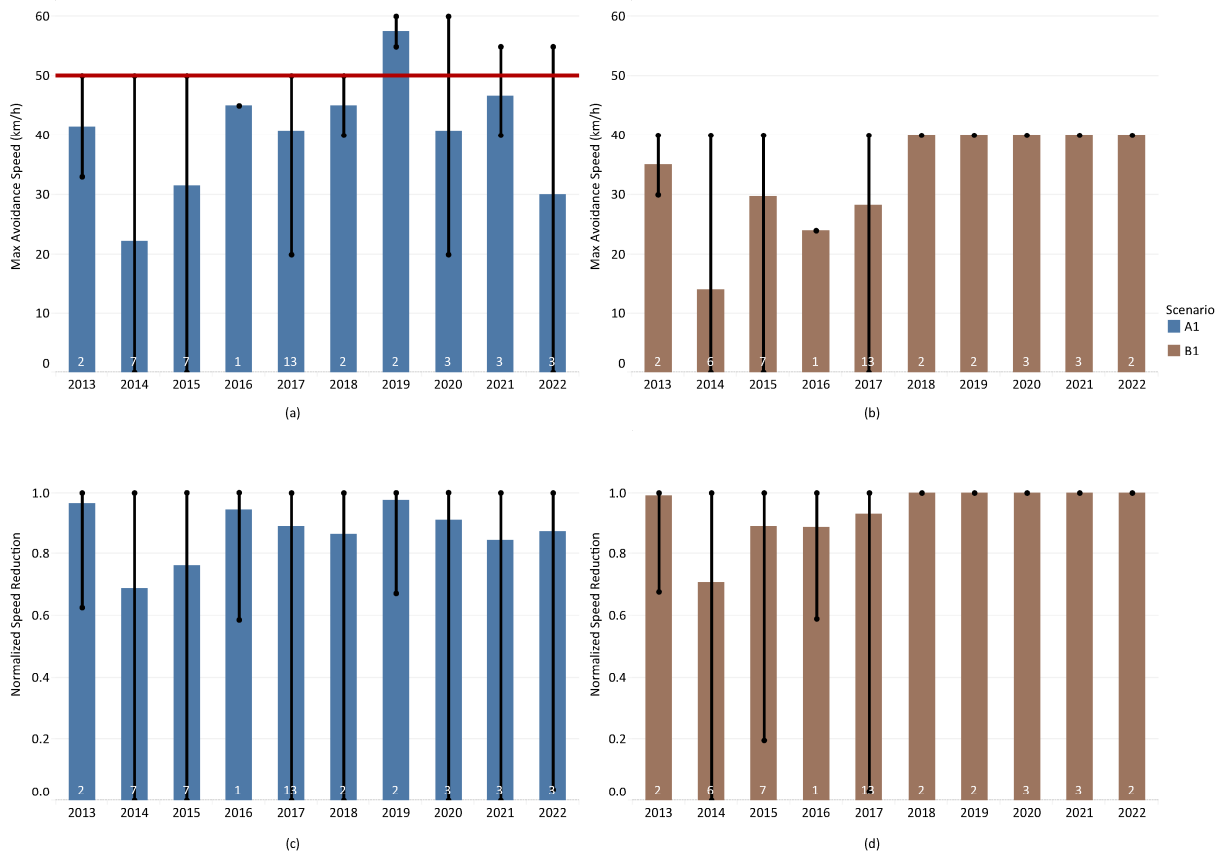


Figure 4. Normalized Speed Reduction and Maximum Avoidance Speed per Model Year for C2C Scenarios

As was the case for the C2C scenarios, the C2P adult and child pedestrian scenarios also saw a rise in maximum avoidance speeds up to 2019 (Figure *5*a and Figure *5*b respectively). After which, the results varied by type of scenario. The R152 Par. 6.6 scenario had a large decrease in performance from 2019 to 2020, but then increased again in 2021, while the CPNC remained within 10 km/h from 2020 to 2022. In terms of normalized speed reduction, there was an increase to over 95% for the adult and over 85% for the child in 2019 (Figure *5*c and Figure *5*d respectively). After which, the normalized speed reduction remained high (between 85% to 90% for the adult and 75% to 90% for the child).
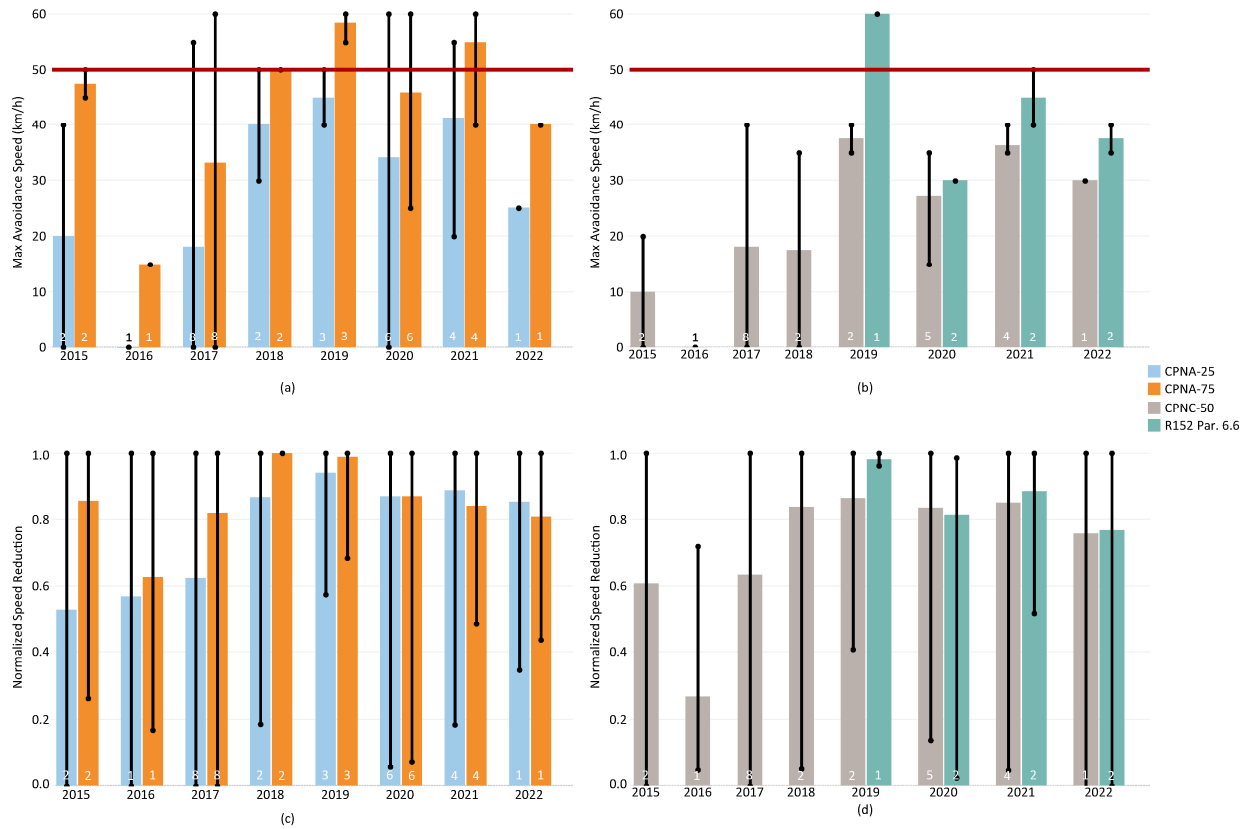
Figure 5. Normalized Speed Reduction and Maximum Avoidance Speed per Model Year for C2P Scenarios

Subaru, Kia, Honda and Hyundai were in the top performers for the C2C A1 scenario, all reaching average maximum avoidance speeds over 45 km/h (Figure *6*a). In the C2C B1 scenario, 9 out of 23 reached the full maximum avoidance speed tested (40 km/h) (Figure *6*b). The four top performers in the A1 scenario were also part of the nine manufacturers that achieved maximum avoidance speed in the B1 scenario. The normalized speed reduction results (Figure *6*c and Figure *6*d) show that most manufacturers achieved a speed reduction of more than 80% (63% for A1 and 52% for B1).
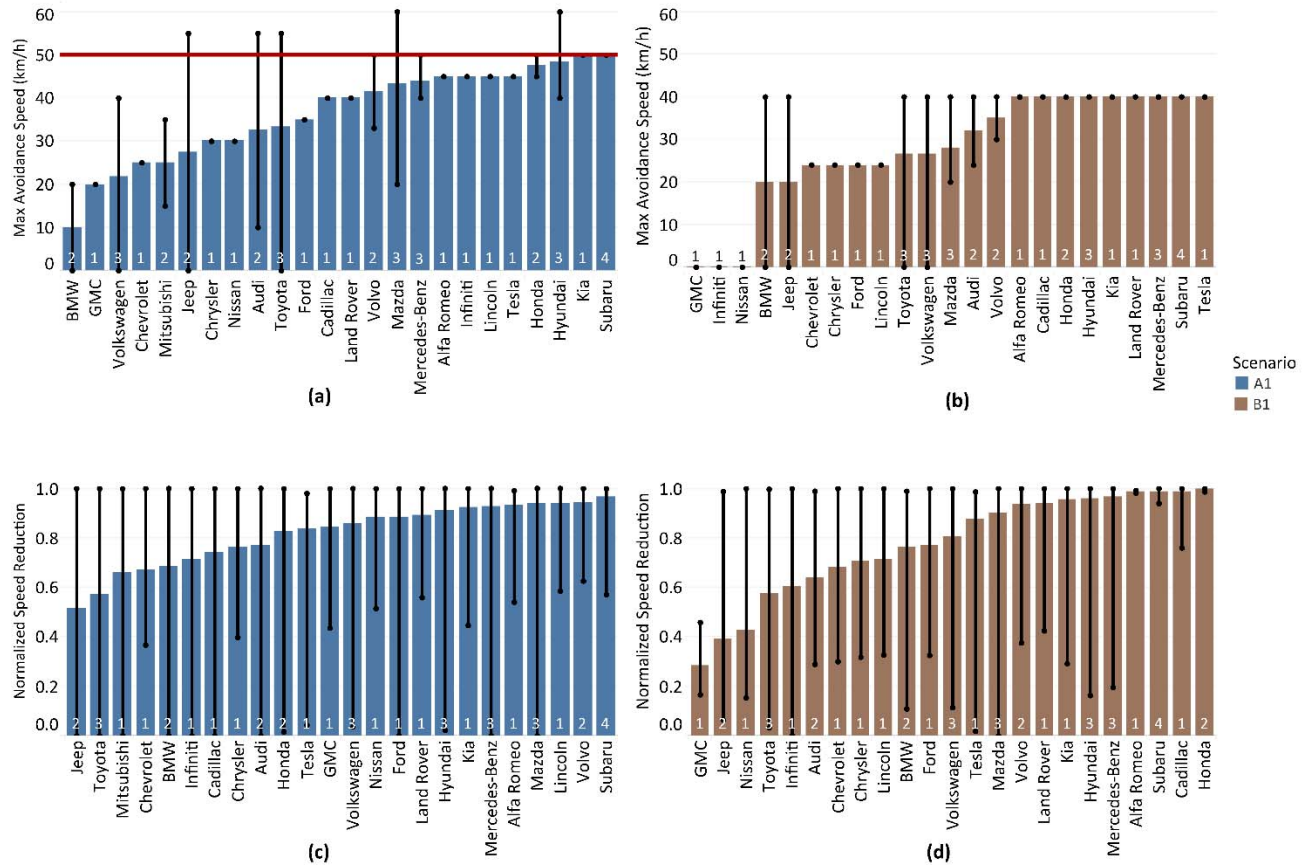
Figure 6. Normalized Speed Reduction and Maximum Avoidance Speed per Manufacturer for C2C Scenarios

Seven manufacturers (BMW, Genesis, Mazda, Mercedes-Benz, Subaru, Tesla and Volvo) reached the maximum avoidance speed tested (50 km/h) for the CPNA-75 scenario, with six of them even reaching higher speeds, while only two manufacturers (BMW and Tesla) reached the maximum avoidance speed of 50 km/h for the CPNA-25 scenario (Figure 7a). With the child pedestrian (Figure 7b), Chevrolet, Volvo and Genesis reached the highest avoidance speeds (40 km/h, 35 km/h and 35 km/h respectively) for the CPNC-50 scenario, while Audi and Genesis reached the highest speed for the UN R152 scenario (60 and 50 km/h respectively). In the scenarios with the adult target (Figure 7c), 72% of manufacturers had a normalized speed reduction above 80% in the CPNA-75 scenario while 55% reached this level of reduction in the CPNA-25 scenario. On the other hand, in the scenarios involving the child target (Figure 7d) only 38% of manufacturers achieved at least 80% speed reduction when the target was occluded (CPNC-50) and 57% when unobstructed (UNECE R152 Par 6.6).
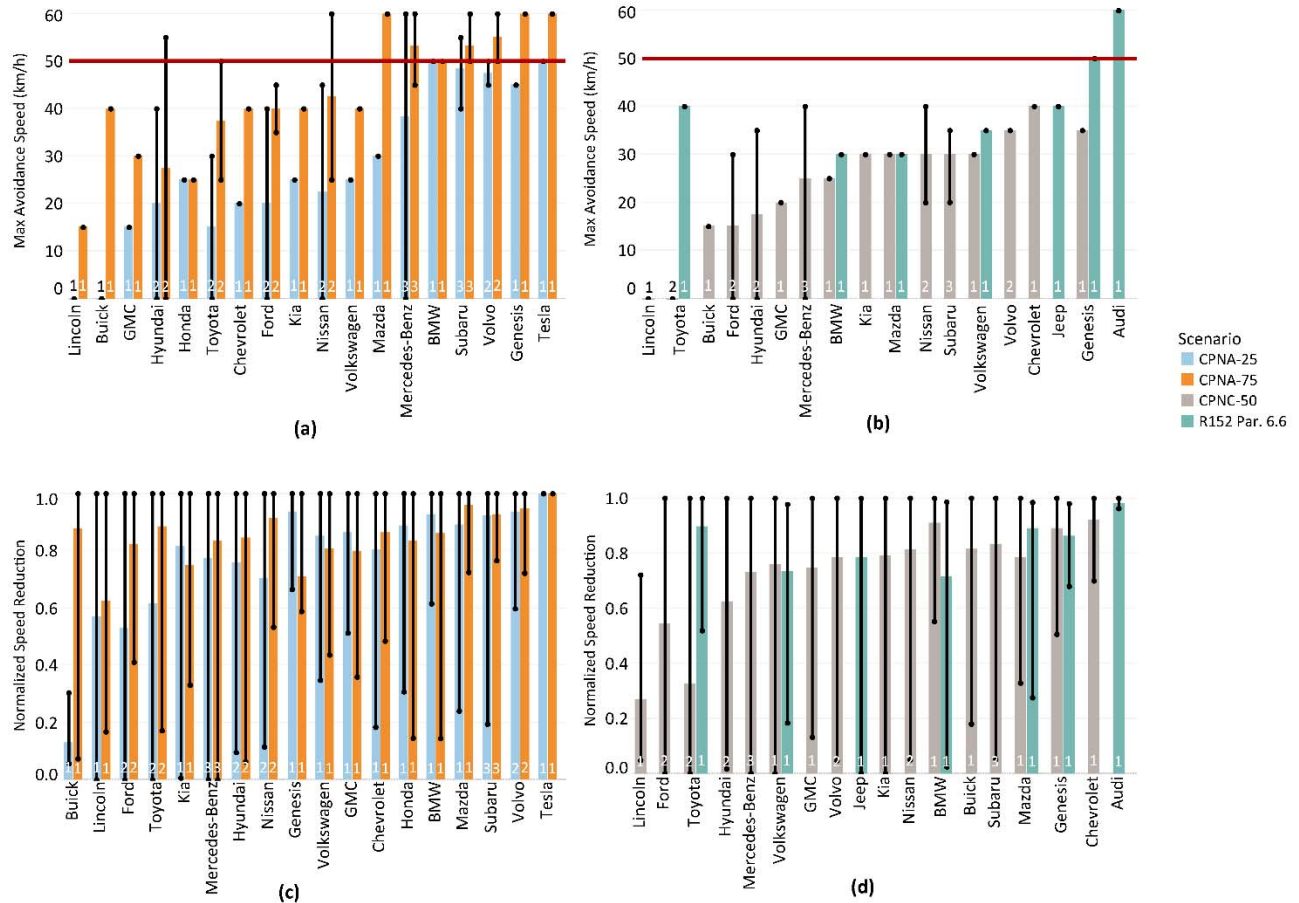
Figure 7. Normalized Speed Reduction and Maximum Avoidance Speed per Manufacturer for C2P Scenarios

## DISCUSSION

The goal of this study was to evaluate the performance of AEB car-to-car and car-to-pedestrian systems available in vehicles and their evolution over time. The study evaluated the systems based on currently published performance criteria (UN R152 and US AEB) and looked at how they performed relative to one another. Finally, relevant Canadian road injuries and fatalities and corresponding vehicle speeds were examined to determine if the performance of current AEB systems has the potential to reduce those numbers or if a gap remains to be addressed.

Performance criteria differ between the UN and US requirements. The UN Regulation, which includes requirements for both C2C and C2P AEB, was published after the US AEB and thus considers newer AEB technology available in Europe. As well, the differences in scope of the requirements translate to a higher success rate when comparing the A1 scenario results of the tested vehicles evaluated against the US AEB Option A versus the UN R152. However, it should be noted that while test performance thresholds are relevant to safety, they may not directly translate into a reduction of the risk of collisions in the real world if these thresholds are set too low. On the other hand, if these performance thresholds are set too high, they may be unattainable by many systems or the costs of reaching such thresholds may exceed the benefits.

Also, the number of test repetitions required by the test protocol can be a factor in determining vehicle performance. The US AEB approach, which takes the average of 5 repeated tests, can dilute the robustness of the system by averaging results as compared to the single test requirement of the UN R152 protocol. Since AEB is an emergency device, the robustness and reliability of a system should be considered in the design of a test to reflect the spontaneity of AEB activation in the real world.

For both C2C and C2P tests, vehicle performance appears to improve over the years, as manufacturers began offering systems able to perform above the minimum requirements of the US AEB and that perform well per UN R152. In fact, before 2019, the best performing systems would only be tested up to speeds of 50 km/h as the impacts with the target were more frequent and to reduce potential damage to equipment. As time progressed, confidence in testing at speeds higher than 50 km/h also increased.

The availability of systems in North America has also been on the rise, with previously-rare systems such as AEB with pedestrian detection (P-AEB) becoming more readily available. Given that pedestrians accounted for 15.2% of road fatalities in Canada in 2020 [3], the introduction of such systems can help in reducing pedestrian fatality risk. Due to the rarity of P-AEB in earlier years, evaluations were limited for C2P scenarios. Furthermore, the P-AEB systems would only slightly reduce vehicle speed before an impact and only luxury vehicles performed well (e.g., Mercedes, Volvo).

When evaluating the system responses to the different C2P scenarios, the Euro NCAP CPNC-50 was found to be the most challenging due to the limited direct visibility (the pedestrian is obstructed by two parked vehicles up until the last instant). This scenario is also believed to represent the most realistic urban scenario, in which pedestrians are at greater risk. The performance has evolved, with avoidance speeds going from below 20 km/h to above 25 km/h in the later years (2019 and later). If the trends continue, vehicles that offer P-AEB are expected to improve even further over the next few years.

The increased performance trend in C2C scenarios is an indicator of the technological advances that have occurred since the start of this test program. As such, the percentage of vehicle models that meet the requirements is expected to increase as AEB technology matures, thus paving the way for more stringent performance criteria. In fact, the slower moving lead vehicle scenario (B1) shows that the technology of all tested systems has surpassed the requirements since 2016.

Although not presented in the figures, some systems performed full stops in the slower moving lead vehicle scenario (B1), which exceeded the deceleration needed to avoid an impact. If a following vehicle is not equipped with a similar system or has an inattentive driver, this AEB overreaction could increase the risk of rear-end collisions. A safer response would likely be to reduce speeds to match the lead vehicle's speed. More research is needed to investigate this issue of excessive AEB braking responses.

Some model years, such as 2013, 2019 and 2022 stand out from the overall observed trend as they show significantly higher (2013 and 2019) or lower (2022) performance. The small sample size for these years amplifies the effect of the difference in technology performance observed between different manufacturers. In 2013 and 2019 the tested vehicles were made by manufacturers that are consistently at the higher end of the performance spectrum. In 2022, one vehicle which had significantly lower performances, contributed to reduce the average level for that model year.

As vehicle performance is likely to increase due to the evolution of sensor technologies and detection algorithms, considerations for a wider prescribed requirement would be beneficial to help reduce the risks at higher speeds. Based on the results, some of the latest models can avoid collisions at speeds up to 60 km/h for C2C as well as some C2P configurations. Setting the bar to a higher speed of operation would address a larger portion of the on-road risk. In fact, when looking at the collision data, speeds up to 69 km/h capture 70 % of injuries and 40 % of fatalities of rear-end collisions (Figure 1), and over 95 % of injuries and 60 % of fatalities of pedestrian collisions (Figure 2). Therefore, setting minimum requirements to 60 km/h for both C2C and C2P could have the potential of addressing the majority of injuries occurring on the roads and seems attainable by most vehicle manufacturers at this time. As AEB technology continues to progress, performance requirements could be set to even higher speeds in the future.

Testing at several speeds in a given range, as currently done in UN R152, enables an assessment at lower city speeds (as low as 10 km/h) and higher speeds (up to 60 km/h) for the C2C scenarios. This also ensure that systems work at all speeds and not just at higher speeds. As for the C2P, a similar approach should be taken for scenarios in which the systems have a better view of the target, leaving adequate time for the vehicle to react. Gradually pushing the upper limit of performance appears to be a logical path when comparing results to the current procedures available for the evaluation of AEB.

It is important to note that the test samples were not random. Vehicles were selected based on the models' sales volume (popular models), new technology offered, availability, cost, and to represent different manufacturers. Although the large sample size of this study means the results are more representative of the Canadian vehicle fleet, the distribution over the years and by manufacturer limit the analyses possible. In other words, if a model year contained more vehicles from the top performing manufacturers, the results would be skewed for that specific year. Similarly, the number of tests performed was not equally distributed between the years and by manufacturer. Certain averages contained a small number of vehicles whereas others contained a larger number.

Finally, the statistics presented in Figure 1 and Figure 2 represent collisions occurring on Canadian roads in diverse weather, road conditions and crash configurations. Only a small subset of conditions is represented by the test methods used in this study, which focused on ideal conditions. Also, the data do not include the severity of injuries, which would be valuable information when determining priorities in scenarios and prescribing test speeds. Nevertheless, the collision data presented gives an indication of the current landscape and can help setting targets to improve road safety for all.

Transport Canada will continue to evaluate the safety performance of the latest crash avoidance systems to identify risks and opportunities to improve safety. Specifically, AEB systems will be tested at higher speeds, with different vehicles targets, under different configurations (e.g., nighttime, intersection, rain, snow) and using real-world driving behaviour (e.g., allowing more steering and accelerator inputs compared to the small tolerances of test standards).

## CONCLUSIONS

Most vehicles tested since 2013 were able to mitigate rear-end crashes according to the criteria defined in the US AEB protocol while less than a third met the UN R152 requirement for the stopped lead vehicle condition and half for slower moving lead vehicle scenario. The car-to-pedestrian configurations were found more challenging overall with better mitigation for the adult pedestrian crossing from nearside to a predicted impact point at 75% of the vehicle width. The worst AEB performance were observed for the occluded child scenario. Overall, the AEB performance, characterized by the speed reduction and the maximum avoidance speed, progressed over the years with more systems now capable of exceeding the requirements defined in the selected protocols.

The best performing AEB systems could avoid a collision at speeds (0-60 km/h) where a considerable number of casualties occur (49% pedestrian fatalities, 30% rear-end crash fatalities). This represents significant progress for systems that should help improve road safety. As AEB systems continue to advance, it is expected that not only the maximum avoidance speed will increase but the range of scenarios and crash configurations will expand (e.g., nighttime, intersection, rain, snow) to address a wider range of real-world risks.

Transport Canada's assessment capabilities have evolved since the early days of AEB performance testing. By using state-of-the-art equipment, novel methodologies and innovative test scenarios, emerging technologies available to Canadians will continue to be evaluated to determine the implications they have for safety and their potential contribution to help reaching zero road casualties.

## ACKNOWLEDGEMENTS

## DISCLAIMER

The authors report that there is no competing interest to declare, testing facility and equipment is property of Transport Canada and vehicles were purchased by Transport Canada for the sole purpose of research activities. The brands and models selected were part of a research fleet available to the department and were purchased through a

competitive process without the manufacturer's knowledge. The observations made in this report are the sole expression of the authors and do not necessarily reflect Transport Canada's policies and regulations.

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