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Rear-End Collision Analysis and Time-to-Collision Based FCW/AEB Design

Prakash Raju Sridharraju | prakashr@student.chalmers.se

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Introduction

This project investigates critical rear-end collision scenarios and driver braking behaviour using a combination of physics-based modelling and experimental data analysis. Time-domain simulations and time-to-collision-based metrics are used to evaluate stopping distances, reaction times, and braking aggressiveness. A data-driven braking-event detection algorithm is developed in Python to extract safety metrics such as TTC, brake-onset speed, and deceleration levels from test-track datasets. These results are then used to design and evaluate Forward Collision Warning (FCW) and Autonomous Emergency Braking (AEB) strategies for simplified Euro NCAP car-to-car stationary scenarios.

Active safety Context

Rear-end crashes are among the most frequent collision types, often caused by delayed driver reactions and insufficient braking. Understanding how drivers actually brake in critical situations, and how much TTC margin they use, helps engineers specify FCW/AEB activation thresholds that balance safety with driver acceptance. By linking measured driver behaviour to simplified vehicle dynamics and stopping-distance models, this project illustrates how active safety functions can be tuned to typical and extreme human responses, rather than relying solely on idealised assumptions.

Keywords: Time-to-Collision, rear-end collision, Forward Collision Warning, Autonomous Emergency Braking, driver behaviour analysis

Baseline Braking Analysis

Baseline stopping distance calculation

Data:

$$\text{Vehicle speed } (v) = 90 \text{ km/h} = 25 \text{ m/s},$$
$$\text{Driver reaction time } (t) = 1.5 \text{ s},$$
$$\text{Deceleration } (a) = -5 \text{ m/s}^2.$$

During reaction time, the car covers the distance:

$$d_r = v \times t = 25 \times 1.5 = 37.5 \text{ m} \tag{1}$$

During braking, the car covers the distance:

$$d_b = \frac{v^2}{2a} = \frac{25^2}{2 \times 5} = 62.5 \text{ m} \tag{2}$$

The minimum distance at which the driver needs to start braking to avoid a collision:

$$d_{\min} = d_r + d_b = 37.5 + 62.5 = 100 \text{ m} \tag{3}$$

Time-to-Collision estimation for baseline case

Time-to-collision (TTC): TTC tells us how long it takes for the car to travel, at its current velocity, to end up in a rear-end collision. From Question 1, this can be calculated as follows:

$$TTC = \frac{d_b}{v} = \frac{62.5}{25} = 2.5 \text{ s} \tag{4}$$

Therefore, the driver would have ended up in a rear-end conflict in 2.5 seconds, given no acceleration.

Impact speed estimation for reduced headway

The driver identifies the approaching threat at a range of

$$d_{\text{range}} = 90 \text{ m}.$$

(i) Reaction distance

From Question 1, the reaction distance was already calculated as

$$d_r = 37.5 \text{ m}.$$

(ii) Remaining distance for braking

$$d_{\text{remain}} = d_{\text{range}} - d_r = 90 - 37.5 = 52.5 \text{ m} \tag{5}$$

(iii) Braking distance required

From Question 1, the minimum braking distance required to stop was found as

$$d_b = 62.5 \text{ m}.$$

(iv) Comparison

$$d_{\text{remain}} = 52.5 \text{ m} < d_b = 62.5 \text{ m} \tag{6}$$

Hence, the remaining distance is less than the minimum braking distance required to stop, and the collision is inevitable.

(v) Collision speed

$$v^2 = v_0^2 + 2ad_{\text{remain}} \tag{7}$$

Substituting the values:

$$v^2 = 25^2 + 2(-5)(52.5) = 625 - 525 = 100,$$
$$v = \sqrt{100} = 10 \text{ m/s} \approx 36 \text{ km/h} \tag{8}$$

The driver would need 100 m to stop safely, but only 90 m is available. A collision will occur at approximately 10 m/s (36 km/h).

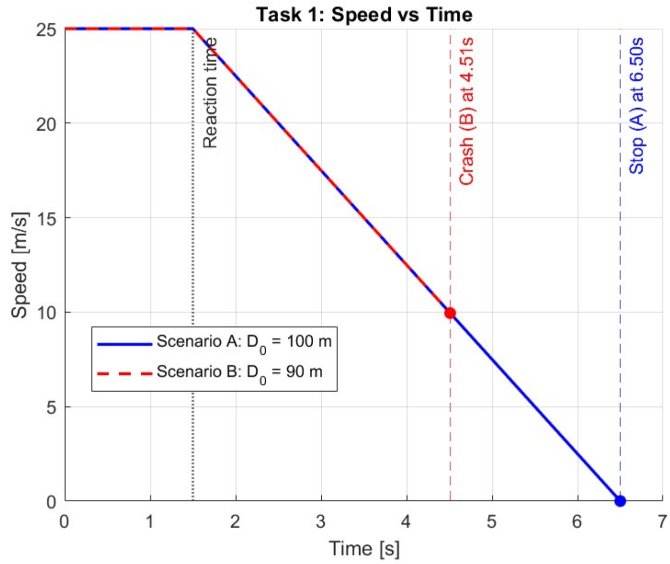

Figure 1: Speed vs Time curve of the vehicle under different conditions.

Speed and relative-distance profile interpretation

In Fig. 1, we can observe the Speed vs Time curve of the vehicle driven under different conditions as explained in the previous sections. First, we can observe the solid blue line, which describes the braking condition when the lead vehicle is at a distance of 100 meters. We can see that the vehicle is travelling at a constant speed of 25 m/s (90 km/h) for the first 1.5 seconds. This depicts the reaction time of the driver. As the driver applies braking at a rate of $-5\ \mathrm{m/s^2}$, the speed is reduced to 0 at exactly 6.5 seconds, and the vehicle travels 100 meters during this driving scenario.

The dashed red line represents the scenario where the lead vehicle is at a distance of 90 meters from the test vehicle before the driver observes it. In this condition, the vehicle will cover the 90 meters distance in 4.5 seconds and will hit the lead vehicle at a speed of 10 m/s (36 km/h).

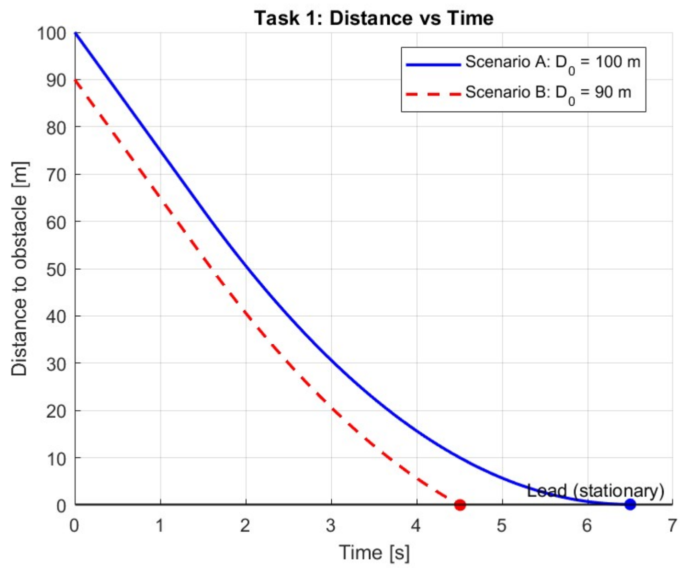

Figure 2: Closing distance between the test vehicle and the stationary lead vehicle.

In Fig. 2, we can see the plot showing the closing distance between the test vehicle and the stationary lead vehicle. As observed, both the dashed red curve (starting relative distance = 90 m) and the solid blue curve (starting relative distance = 100 m) have a linear steep slope during the initial 1.5 seconds. This is due to the vehicle travelling at constant speed, representing the reaction time of the driver. As the vehicle decelerates, we can observe the steepness of the curve decreasing.

The red curve drops to 0 m at 4.5 s, which indicates a collision. In contrast, the blue curve reduces steadily and reaches 0 m exactly when the test vehicle has already stopped.

Experimental Data Processing and Braking Event Detection

To gain a better understanding of the data that was available, the data was manually examined after being imported. This led to few important conclusions. First of all, there were numerous missing values in the radar data (range, range rate, and acceleration), whereas the corresponding vehicle's acceleration and speed information was complete. Secondly, the time data from the radar and the vehicle were nearly synchronized, with an average variance of roughly 200 milliseconds. The recorded data instances were collected every 100 milliseconds. Thirdly, the speed and acceleration data from the vehicle and radar were nearly identical, thus a vehicle speed of x would correspond to a radar range rate of -x.

The next step was to preprocess the raw data. We first converted the dataset into a NumPy array. After that, we removed all rows where no radar range was detected. We also discarded entries containing only minimal radar range information. Our main assumption is that without sufficient radar range data, further calculations cannot be performed. This is because most of the safety metrics, such as, range at brake onset, TTC depend on radar measurement of distance and relative speed to the lead object. If the radar measurements are too messy or sparse, then it is difficult to determine how close the vehicle was to another object or how quicklt it is approaching. In such cases, the computed safety metrics would not make any sense. So, to ensure consistency, we required a minimum of 60 valid radar points and 60 valid speed points in each test run. After applying this condition, 60 valid runs remained in the dataset. Also, we synchronized the vehicle and radar timestamps.

To automatically detect braking maneuvers, we developed an algorithm based on vehicle speed and acceleration. First, the speed signal was smoothed using a Savitzky–Golay filter to remove noise while keeping the trends. From this smoothed signal, acceleration was computed and smoothed again. A dynamic threshold was then defined as either -0.5 m/s^2 or 1.5 standard deviations below the mean acceleration, whichever was lower. All time points below this threshold were grouped into continuous segments. Only segments lasting at least 0.2 seconds were considered as valid braking maneuvers. Among these, the segment with the most negative acceleration (maximum deceleration) was selected as the braking event. We used this algorithm to all runs, successfully identifying braking.

To visualise the performance of our braking detection algorithm, we plotted each test run with vehicle speed and acceleration. Each figure contains two subplots. Figure 3 shows an example result, where the upper subplot displays the vehicle speed over time, and the lower subplot shows the corresponding smoothed acceleration. The start and end of each detected braking maneuver are marked with vertical dashed lines: red for the brake onset and green for the brake end. This allows for a clear visual verification of the detected braking events against the underlying speed and acceleration signals. All plots were saved for further inspection, ensuring that the algorithm correctly identifies braking maneuvers across multiple test runs. Figure examples (submitted in a zip file) illustrate that the algorithm captures the main deceleration periods and avoids false detections due to noise in the vehicle speed or acceleration signals.

Once braking maneuvers were identified, the next step was to extract key safety-relevant metrics for each maneuver. For each detected braking event, the following parameters were computed:

(i) Brake onset speed – the vehicle speed at the start of the braking maneuver.

(ii) Brake onset range – the radar-measured distance to the lead object at the start of braking. When radar range values were missing, linear interpolation was used between neighboring radar points to estimate the range at the exact brake onset time.

(iii) Mean acceleration – the average vehicle acceleration during the braking maneuver, computed from the smoothed acceleration signal.

(iv) Maximum deceleration – the minimum acceleration during braking, corresponding to the peak braking effort.

(v) Time-to-collision (TTC) – calculated as the ratio of brake onset range to the closing speed (negative radar range rate) when available. TTC was set to infinity if radar data was missing or if the vehicle was moving away from the lead object.

The metrics were computed for all valid runs. If a braking maneuver could not be detected in a particular run, all metrics for that run were recorded as NaN.

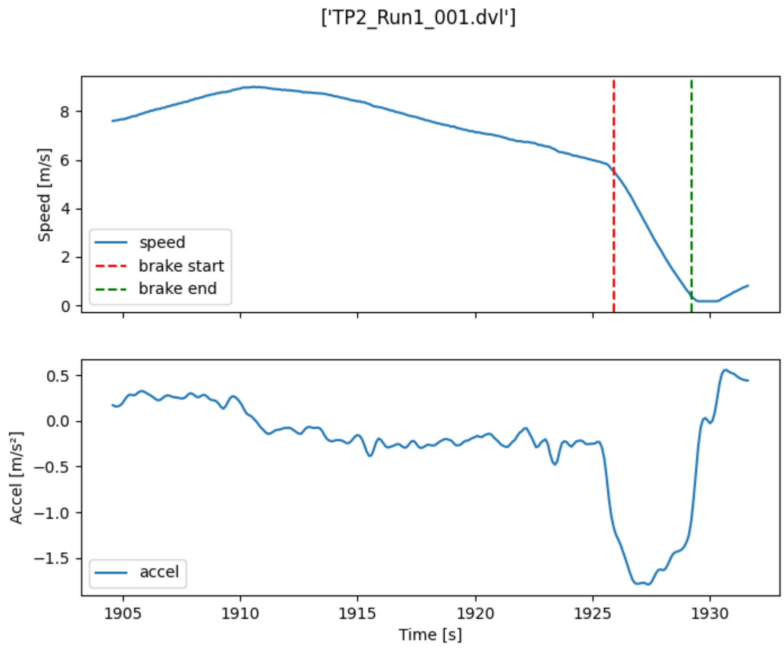

Figure 3: Visualisation of the braking detection algorithm for one test run.

Driver Braking Behaviour Characterisation

Speed at brake onset vs. TTC per driver

We started by analyzing driver behavior using the dataset provided after the midterm submission. In the first task, the goal was to investigate the relationship between the **Speed at Brake Onset** and the **Time-To-Collision (TTC) at Brake Onset** for each participant.

The dataset contained a total of **73 entries**, collected from **9 participants**. To analyze the data, we used the `unique` command in our code to automatically detect all participants in the dataset.

For visualization, we implemented a plotting routine that:

- Automatically identifies all unique participants.
- Creates one subplot per participant.
- Displays the individual relationship between **Speed at Brake Onset (x-axis)** and **TTC at Brake Onset (y-axis)**.

This approach helped us to get clear comparison of braking behavior across all participants, providing insights into the variability in driver responses to potential collision scenarios.

The figure above illustrates the scatter plots for all nine participants. Each subplot shows how the **TTC at Brake Onset** varies with the **Speed at Brake Onset**, highlighting participant-specific driving behaviors and braking response patterns.

Clustering of TTC behaviour across drivers

Analysis of TTC and Speed Relationship The next task was to use the Figure 4, and analyze whether the different participants exhibited both high and low TTC values, or if their data showed any clustering patterns. From the plots, we came to a conclusion that each participants displayed varying TTC values at different speeds.

For instance, **Participant 2** showed relatively high TTC values, reaching approximately **5 seconds** at a speed of around **16 m/s**, and about **2 seconds** at lower speeds (around 2 m/s). This suggests that Participant 2 tended to maintain a larger safety margin and responded more cautiously.

In contrast, some participants exhibited clusters in their data:

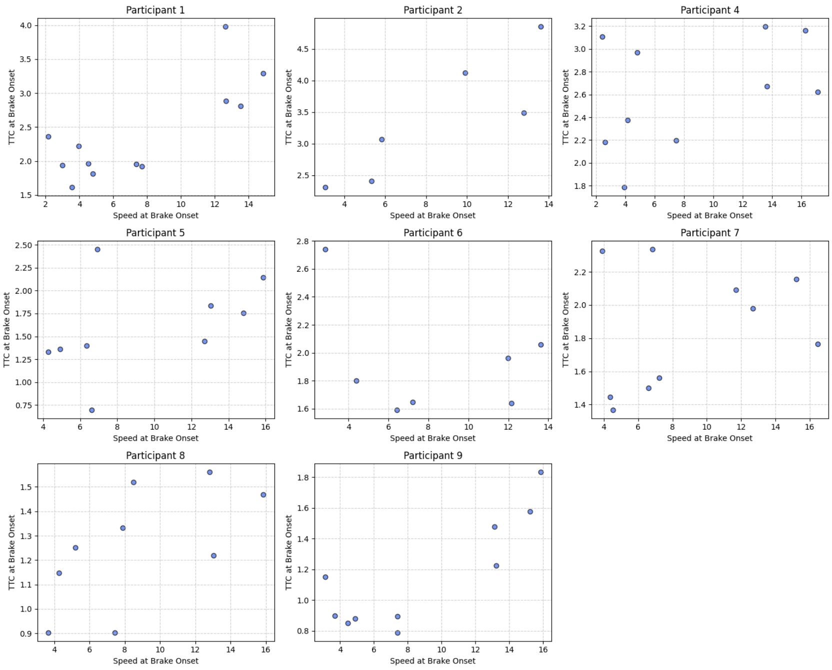

Figure 4: Speed at Brake Onset vs. TTC at Brake Onset for each participant. Each subplot represents one driver.

- **Participant 1, 7, and 9** showed noticeable clustering, where most TTC values were concentrated in a narrow range. For example, Participant 1 had TTC values around **1.5–2 seconds** at speeds between **2–6 m/s**, and TTC increased as speed rose.
- This clustering indicates consistent braking behavior at certain speeds, suggesting similar reaction tendencies during the braking onset.

Overall, the plots reveal that while some drivers (like Participant 2) demonstrated a wider range of TTC values, others maintained consistent or clustered TTC behavior, showing individual differences in driving caution and reaction timing.

TTC distribution and percentile statistics

Histogram and Statistical Distribution of TTC In the next task, we plotted histogram to visualize the distribution of **Time-To-Collision (TTC)** at brake onset for all participants combined. The histogram provides insight into the overall distribution of TTC values across different drivers and braking scenarios.

The resulting histogram (Figure 5) shows a **positively skewed** distribution. This indicates that most braking events occurred at **shorter TTC values** (i.e., when drivers were relatively close to a potential collision), while only a few events occurred at **higher TTC values**, where braking was initiated earlier and more cautiously.

This pattern suggests that the majority of drivers tend to brake later rather than sooner, exhibiting more reactive rather than preventive braking behavior.

The 5^{th} and 95^{th} percentiles of the TTC distribution were computed to describe the spread of the data:

$$\text{5th percentile of TTC} \approx X \ 0.89 \text{ s}, \quad \text{95th percentile of TTC} \approx Y \ 3.37 \text{ s}.$$

This means that approximately 90% of all braking responses occur within this range, capturing the central tendency of driver reaction behavior.

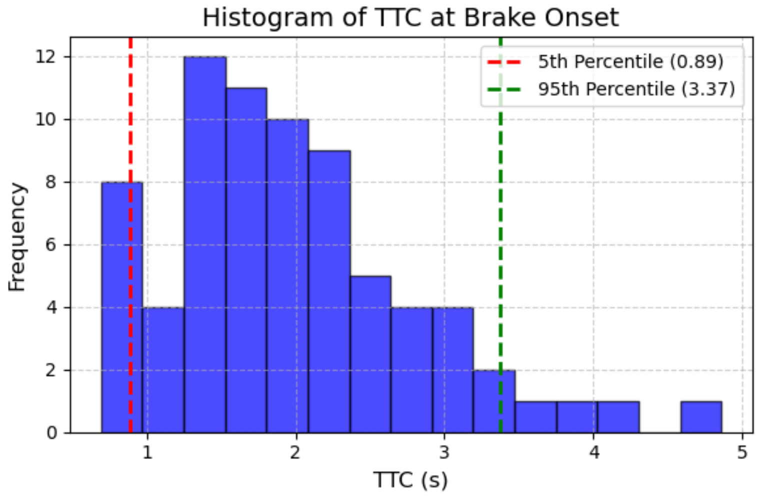

Figure 5: Histogram of Time-To-Collision (TTC) at Brake Onset for all participants combined, showing a positively skewed distribution. Most braking events occur at lower TTC values, indicating late braking behavior.

TTC-based active safety threshold selection

Time-To-Collision (TTC) is an important metric used in vehicle safety systems. It estimates how much time remains before a collision would occur if neither the driver nor the vehicle takes action (such as braking or steering). A lower TTC indicates a more critical situation, while a higher TTC means there is more time to react.

When designing an active safety system such as a collision warning or automatic emergency braking system, the TTC threshold (the value at which the system reacts) must be chosen carefully.

Defining Driver Types

To decide when the system should activate, we can consider three general driver types as mentioned in the question:

- **Average Driver:** Reacts at moderate TTC values, typically around the mean or median of the data. Example: If the average driver brakes when TTC ≈ 2 s, the system could issue a warning slightly earlier (around 2.5 s).
- **Most Careful Driver (Conservative Cautious System):** Brakes earlier at higher TTC values (e.g., 3–4 s).
  - **Pros:** Safer and less likely to miss dangerous events.
  - **Cons:** May produce frequent false alarms, which can annoy drivers.
- **Sensation-Seeking Driver (Aggressive System):** Brakes later at lower TTC values (e.g., 1–1.5 s).
  - **Pros:** Fewer false alarms and better acceptance by risk-tolerant drivers.
  - **Cons:** Higher collision risk due to delayed reactions.

Choosing a TTC Threshold

From the data analysis, the TTC distribution was found to be **positively skewed**, meaning most drivers brake at shorter TTC values, while a few brake much earlier. A practical approach is to use the **5th and 95th percentiles** to describe driver behavior (based on previous question):

$$\text{5th percentile} \approx 0.89 \text{ s} \quad \text{(very late braking)}, \qquad \text{95th percentile} \approx 3.37 \text{ s} \quad \text{(very early braking)}$$

A balanced threshold for the active safety system could therefore be set around the **mean or median TTC** (approximately 2 s). This value provides a good trade-off between early warnings and avoiding false alarms, ensuring that the system is suitable for most drivers.

Braking acceleration distributions and driver types

Figure 6 shows the distributions of mean and minimum acceleration for all drivers. The **mean acceleration** plot shows that most drivers had values around -3 m/s^2, meaning they used moderate braking on average. A few drivers had much lower values (around -6 to -7 m/s^2), which indicates very strong braking. This suggests that most drivers brake smoothly, but some react late and must brake harder.

The **minimum acceleration** plot shows the strongest deceleration during each braking event. The data has two peaks: one near -3 m/s^2 and another near -8 m/s^2. This means there are two main types of drivers: careful drivers who start braking early and gently, and aggressive drivers who brake late and strongly.

Overall, these results show that drivers behave differently when braking. Some are cautious and react early, while others wait longer and then brake hard. Understanding these differences is important when designing safety systems that should work well for all types of drivers.

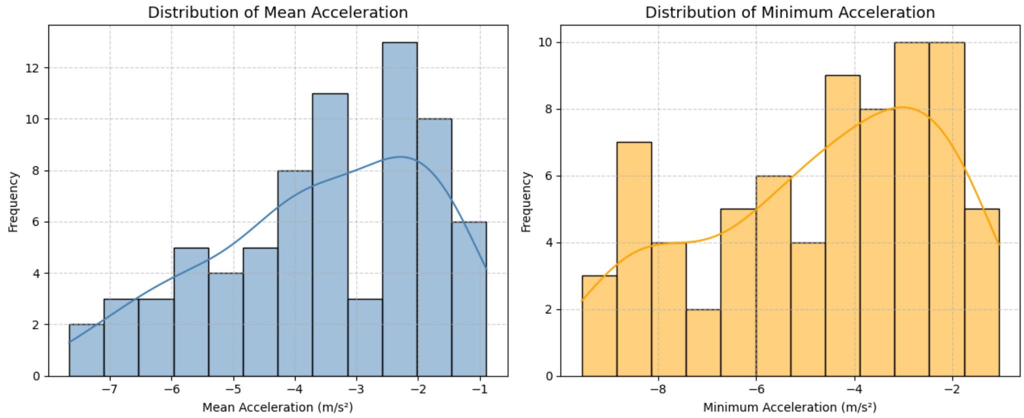

Figure 6: Distributions of mean and minimum acceleration across all drivers.

Forward Collision Warning and AEB Concept Design and Evaluation

FCW threat-assessment logic and parameterisation

The calculated safety metrics can be used to estimate the upper and lower limits of driver braking behavior in critical rear-end situations. Based on these results, we now propose two Forward Collision Warning (FCW) systems—one **conservative** and one **aggressive**—that could be used for the Euro NCAP car-to-car stationary (CCRs) test. We have assumed driver reaction time as 1.2s and 0.8s for conservative and aggressive driver respectively.

1. Background

We designed an active safety system based on the driver braking analysis with respect to Time-To-Collision (TTC).

$$\text{5th percentile: } 0.89 \text{ s} \quad \text{(very late braking)}$$

$$\text{95th percentile: } 3.37 \text{ s} \quad \text{(very early braking)}$$

$$\text{Median: } \approx 2 \text{ s}$$

These values represent the range of typical human behavior and can be used to design driver-support systems. The input variables for the FCW/AEB systems are:

$$\text{range } (m) \quad \text{and} \quad \text{rangeRate } (m/s)$$

The Time-To-Collision is computed as:

$$TTC = \frac{\text{range}}{|\text{rangeRate}|}$$

2. Threat Assessment

Threat assessment is the process of evaluating how critical the current situation is. It determines whether the closing speed and distance to the lead vehicle imply a potential collision.

In this case:

If TTC is small (below a chosen threshold), the situation is considered critical.

3. Decision Making

Decision making determines when the system should issue a warning (FCW) or take control (AEB). The decision is based on comparing the current TTC to a predefined threshold.

$$\text{If } TTC \leq TTC_{\text{threshold}} \Rightarrow \text{activate FCW (activate} = 1)$$
$$\text{Else } \Rightarrow \text{no warning (activate} = 0)$$

4. Proposed FCW Systems

- **Conservative FCW System**
  - **Threat-assessment:** Considers potential danger early.
  - **Driver Reaction Time:** 1.2 s
  - **Decision rule:** Activates when $TTC \leq 4.5$ s.
  - **Behavior:** Issues early warnings to give more reaction time. Suitable for cautious drivers or lower-speed scenarios.
  - **Pros:** Safer, lower risk of missed warnings.
  - **Cons:** May generate more false alarms.

- **Aggressive FCW System**
  - **Threat-assessment:** Reacts only in critical, near-collision situations.
  - **Driver Reaction Time:** 0.8 s
  - **Decision rule:** Activates when $TTC \leq 2.0$ s.
  - **Behavior:** Issues late warnings, allowing more natural driving for aggressive drivers.
  - **Pros:** Fewer false alarms, more acceptable to confident drivers.
  - **Cons:** Higher collision risk if driver fails to react promptly.

FCW performance in Euro NCAP CCRs scenarios

Speed [km/h]	Cons Activ [m]	Cons Stop [m]	Aggr Activ [m]	Aggr Stop [m]
10	12.5	8.4	4.56	2.56
20	25.0	15.25	11.11	3.58
30	37.5	20.56	16.67	3.06
40	50.0	24.32	22.22	0.99

Table 1: Activation and Stopping Distances for Conservative and Aggressive Modes

In the next task, the two FCW systems were tested under the simplified Euro NCAP Car-to-Car Stationary (CCRs) scenarios at vehicle speeds of 10, 20, 30, and 40 km/h. From previous, the FCW thresholds were set based on driver behavior: **4.5 s** for the conservative system, **3.0 s** for the balanced system (our assumption with **1s** as mean driver reaction time), and **2.0 s** for the aggressive system. Note that the respective driver reaction time is considered. Using the TTC-based activation logic, the threshold was gradually reduced until the vehicle could still avoid a collision in all speed cases.

The results showed that the most aggressive TTC threshold that still allowed safe braking across all scenarios was approximately **1.91 s**. This value is slightly higher than the median threshold of **1.83 s** observed from the driver-behavior analysis in previous sections, indicating that drivers generally brake at the physical limit required for collision avoidance. The aggressive FCW system was designed with a threshold of **2.00 s**, providing a small safety margin above both the driver median and the calculated minimum.

However, during the lowest-speed test (10 km/h), the 2.0 s threshold was found to be slightly conservative. A lower threshold of about **1.08 s** was still sufficient to prevent impact. This difference arises because, at lower speeds, the required stopping distance and braking demand are smaller, allowing later warnings without compromising safety. In contrast, higher-speed conditions require earlier warnings to compensate for longer stopping distances and driver reaction time.

Limitations of FCW-only interventions

- FCW cannot autonomously avoid collisions; it relies on the driver's response
- Effectiveness depends on:
  - driver attention and reaction time (varies significantly)
  - driver willingness to brake hard enough
  - vehicle braking capability and road conditions
- if the driver is distracted, asleep or incapacitated, FCW is ineffective
- False alarms may lead drivers to disable or ignore the system
- Cannot account for evasive manoeuvres (steering)

AEB deceleration requirement and activation logic

Maximum braking capability would highly depend on the friction limits based on the physical laws of motion i.e $F = \mu * MA$, considering $\mu = 0.9$ we get max deceleration as $8.34 m/s^2$. We also verified the the typical emergency braking values between 7-9 m/s from various sources.
Considering this acceleration, we proposed the AEB function for 'Threat Assessment' as

$$a_{\text{required}} = \frac{v^2}{2\,(\text{Range} - \text{margin})} \tag{9}$$

With 'Decision Logic'

$$\text{If } a_{\text{required}} > 8.34 \text{ m/s}^2\text{, then activate AEB.} \tag{10}$$

AEB stopping performance vs. activation range

We have set the safety margin for stop range as 0.5m from the target vehicle. Irrespective of the speed of ego vehicle, AEB will stop the vehicle exactly at a distance of 0.5m.

The function for AEB activation is given by

$$\text{Activation Range} = \frac{v^2}{2\,a_{\text{AEB\_max}}} + \text{safety margin} \tag{11}$$

where $a\_AEB_{max} = 8.3 m/s^2$

Similarly, The function for stopping the vehicle at max AEB is

$$AEB_{\text{acc\_stop\_range}} = Safety\_Margin \tag{12}$$

Speed [km/h]	Activation Range [m]	Stop Range [m]
10	0.96	0.50
20	2.35	0.50
30	4.66	0.50
40	7.90	0.50

Table 2: AEB Acceleration Performance

This table demonstrates that the AEB system dynamically adjusts its activation range with vehicle speed to ensure consistent and safe stopping behavior. The results indicate good system calibration, providing early activation at higher speeds while maintaining a minimal and safe stopping distance.

Speed-dependent TTC thresholds for AEB

In a Time-to-Collision (TTC)-based AEB system, different thresholds are used depending on vehicle speed. At lower speeds (below 54 km/h), the system activates when the TTC falls below 0.9 seconds, while at higher speeds (54 km/h and above), the threshold increases to 1.4 seconds. This is because at higher speeds, the vehicle covers more distance in a shorter time, requiring the AEB system to intervene earlier to ensure enough time and distance to safely avoid or mitigate a collision.

Benefits and Drawbacks
Benefits:

- Earlier activation at higher speeds enhances safety by allowing more time for the driver or system to react, thereby improving collision avoidance performance.
- Adaptive activation thresholds help reduce unnecessary warnings at lower speeds, minimising driver annoyance and improving system reliability.

Drawbacks:

- Fixed threshold settings may not perform well across all driving conditions, such as varying road friction or traffic density, which can reduce system effectiveness.
- Early system activation increases the likelihood of false positives, leading to unnecessary braking or warnings that could reduce driver trust over time.

Unintended AEB activation and required additional inputs

Example: A vehicle is approaching a traffic light where cars are stopped ahead.

In a scenario with unexpected braking, consider a vehicle approaching a traffic light where cars ahead are stopped. The lead vehicle is stationary due to a red light, and the AEB system detects it as a potential collision target within its activation range. Just as the traffic light turns green and the lead vehicle begins to accelerate, the AEB, unaware of the traffic signal, interprets the situation as a threat and triggers emergency braking. This results in unexpected braking, as the driver anticipates the lead vehicle to move forward. To avoid such situations, additional information is crucial, including the target vehicle's velocity and acceleration to predict its motion, traffic signal status through infrastructure or V2I communication, driver intent cues such as accelerator pedal position or braking readiness, the broader scene context (e.g., whether the vehicle is in a parking lot, traffic queue, or intersection), and robust object classification to distinguish between relevant and irrelevant obstacles.

Integrated FCW–AEB behaviour in baseline scenario

Initial Conditions: Vehicle speed: 25.0 m/s
Initial distance to obstacle: 90.0 m

System Responses:

- The Conservative Forward Collision Warning (FCW) activates immediately at t = 0.00 s, when the obstacle is detected at a range of 90.0 m.
- The Aggressive FCW triggers slightly later, at t = 1.8 s, corresponding to a reduced range of 80.0 m.
- The Autonomous Emergency Braking (AEB) system engages at t = 2.10 s, when the vehicle closes in to a 37.5 m distance from the obstacle.

Outcome:

- Without AEB, the vehicle would have collided with the obstacle.
- With AEB, the vehicle successfully comes to a complete stop exactly at 0.0 m from the obstacle, avoiding the collision.

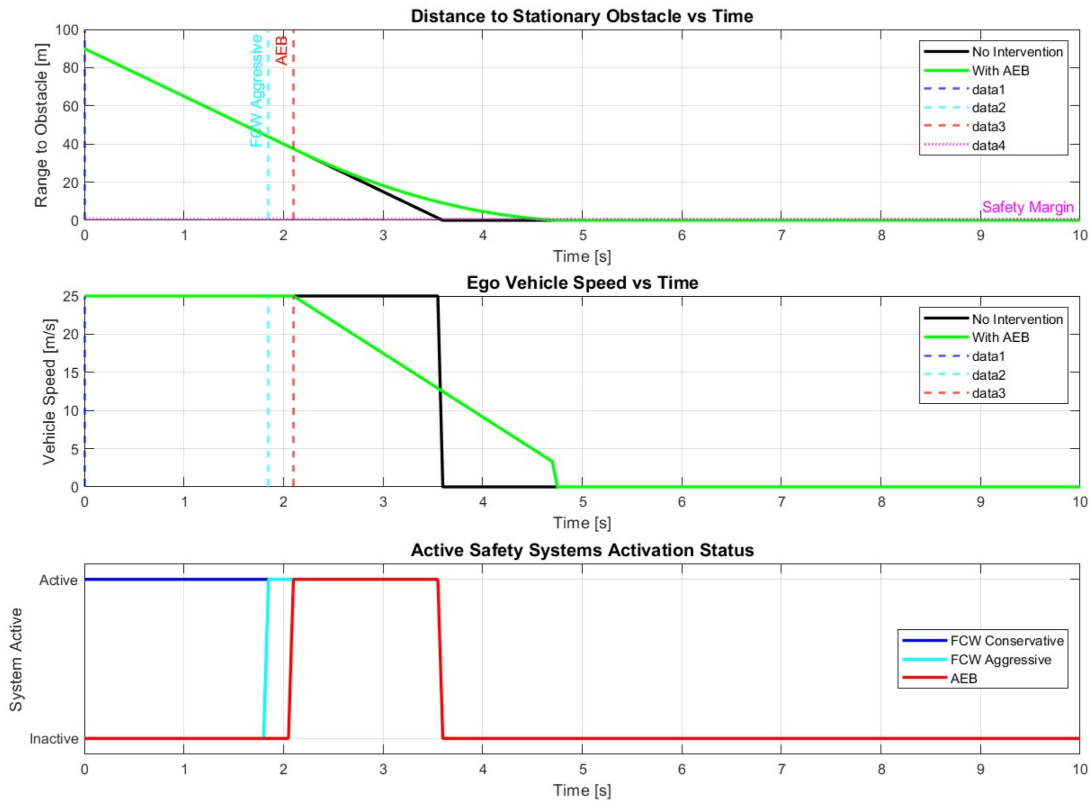

Figure 7: FCW and AEB activation in Task 1 scenario

1) Distance to Stationary Obstacle vs Time Plot
Y-axis: Range to obstacle (m)
X-axis: Time (s)
Black Line (No Intervention): The vehicle continues moving toward the obstacle without braking. The distance steadily decreases to zero, indicating a collision at 3.5s.
Green Line (With AEB): The vehicle detects the obstacle and begins braking automatically. The distance decreases but never reaches zero, means the AEB system prevents a crash.
Blue Dashed Line: FCW warning is triggered early when the system detects potential danger.
Red Dashed Line: AEB system is activated early to prevent collision.
Magenta Dashed Line: Minimum safe distance that should be maintained where AEB ensures the vehicle stays above it.

2) Ego Vehicle Speed vs Time Plot
Y-axis: Vehicle Speed (m/s)
X-axis: Time (s)
Black Line(No Intervention: Speed remains constant until a sudden drop at collision (3.5s)
Green Line(With AEB: Speed starts decreasing sharply after AEB activation (2.1s), reaching zero before collision, showing a safe stop.

3) Active Safety Systems Activation Status Plot
Y-axis: System active/inactive (1 = active, 0 = inactive)
X-axis: Time(s)
Dark Blue Dashed Line(FCW Conservative): Active early, provides a preliminary warning
Light Blue Dashed Line(FCW Aggressive): Activates slightly later, giving a more urgent warning.
Red Line(AEB): Engages around 2s, braking automatically to avoid collision, then deactivates once the vehicle stops safely.

Conclusion

By working on this project, we got an idea of how active safety systems (rear-end collision mitigation) function in real-world driving scenarios. Starting with a hypothetical rear-end collision, we used physics-based approach and Python to explore how reaction time and braking distance affect the rear end collision. Moving on to the second task, we learned about how actual experimental data from test-track is processed and used. Cleaning and processing it was a challenge, but it taught us how to handle real world data imperfections like missing values and time delays. We built an algorithm to detect braking maneuvers and extracted key safety metrics. These metrics gave us a clear idea of how different drivers behave during a potential crash scenario. With those insights, we moved on to the behavioral analysis of different drivers using the data provided to us. We looked at the pattern in the data and observed how different drivers react to potential collision scenarios. We used plots (Speed at brake onset vs TTC at brake onset) to understand the range of responses. This helped us to think about how safety systems should be designed, i.e., considering both conservative as well as aggressive drivers. Finally, we put everything together by designing our own FCW and AEW systems. We created both conservative and aggressive versions, tested them against Euro NCAP scenarios, and evaluated how well they performed. We also explored their limitations and proposed ways to make them smarter and more context-sensitive. In general, the project was a great mix of theory, data analysis, and system design. Each team member contributed to different parts from coding and plotting to writing and reviewing, and we learned a lot by working together. It was a challenging but valuable experience that helped us learn useful skills and better understand how car safety systems work.

Appendix

Formulas Used

1. Time-To-Collision (TTC)

Used in **Forward Collision Warning (FCW)** threat assessment.

$$TTC = -\frac{\text{range}}{\text{rangeRate}}$$

where:

- *range* = distance to the lead vehicle (m)
- *rangeRate* = relative speed (m/s), negative if approaching

If rangeRate ≥ 0, then TTC is undefined (no collision risk).

2. Simulating Driver Stopping Distance:

The total distance a driver travels before coming to a complete stop can be expressed as:

$$d_{\text{stop}} = v \cdot t_r + \frac{v^2}{2|a|}$$

where:

- v = vehicle speed (m/s)
- t_r = driver reaction time (s)
- a = braking acceleration (m/s^2), taken as a positive value

3. Minimum TTC for Safe Stopping:

The minimum Time-To-Collision required to avoid impact must be at least equal to the time it takes to stop safely:

$$TTC_{\min} = \frac{d_{\text{stop}}}{v} = t_r + \frac{v}{2|a|}$$

Function Interpretation:
The stopping distance formula:

$$d_{\text{stop}} = v \cdot t_r + \frac{v^2}{2a}$$

leads directly to the expression for minimum TTC:

$$TTC_{\min} = \frac{d_{\text{stop}}}{v} = t_r + \frac{v}{2a}$$

This relationship defines the minimum reaction time available before a collision becomes unavoidable, forming the theoretical lower limit for FCW or AEB system activation thresholds.

3. Required Deceleration for AEB (Automatic Emergency Braking)

Used to assess whether the vehicle can stop before a collision.

$$a_{\text{req}} = \frac{(\text{rangeRate})^2}{2 \times \text{range}}$$

where:

- a_{req} = required deceleration to avoid collision (m/s^2)
- *rangeRate* = relative speed (m/s, negative if approaching)
- *range* = current distance to the obstacle (m)

4. AEB Activation Condition

The AEB system activates if the required deceleration exceeds the vehicle's maximum braking capability:

$$\text{If } a_{\text{req}} \geq a_{\max} \Rightarrow \text{Activate AEB}$$

where $a_{\max}$ = maximum achievable deceleration (typically 7 m/s^2 on dry asphalt).

5. FCW Activation Condition

The FCW system activates when the current Time-To-Collision is below a defined threshold:

$$\text{If } TTC \leq TTC_{\text{threshold}} \Rightarrow \text{Activate FCW}$$

6. Relation Between FCW and AEB

- **FCW:** Warns the driver before collision (based on TTC).
- **AEB:** Automatically brakes if the driver fails to react (based on a_{req} and $a_{\max}$).

Note: These equations form the foundation of the simplified FCW and AEB logic tested under the Euro NCAP Car-to-Car Stationary (CCRs) scenarios.

References

1. VTS Course Notes, Chalmers University of Technology, 2024.