CMC Basic Specification

Evaluation Report

Systems and applications defined for powered two-wheelers have been verified with prototype vehicles developed in CMC. In this document, methodology for evaluation, test results and analysis results are described.

Document Information

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Disclaimer

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1 Background

C-ITS is a technology based on mutual communication, and its systems and applications need to be aligned between transmitter and receiver. Therefore, the CMC Basic Specification, especially specifications for systems and applications, needs to be verified between transmitter and receiver based on some experimental results.

For the verifications, CMC has developed prototype PTWs with software to test C-ITS systems and some applications. In addition, some cars with the same software were also prepared as the target vehicle of C-ITS communication. Verification was done for some of C-ITS systems and applications.

2 Evaluation tests for C-ITS Applications

2.1 Background

CMC has developed technical descriptions of C-ITS applications which could improve road safety for PTWs. For parameters that are not clearly defined in the technical descriptions, several evaluation tests were planned and performed to determine the appropriate value for these parameters from a scientific point of view. These tests are defined as evaluation tests, and in order to reinforce the basis for setting the appropriate parameters adopted in the technical descriptions of each application, the methods of the evaluation tests and these results and discussions are explained below.

2.2 MAI

2.2.1 About MAI

CMC defines MAI (Motorcycle Approach Indication) and MAW (Motorcycle Approach Warning) which are a set of applications that provide information or warning about an approaching PTW. Please see “Application Specification (Preamble)” for more details about the definition of MAI/MAW.

In the following document, MAI is treated as one application which covers important use cases in intersections including the left turn scenario for PTWs. CMC has developed the MAI application specification as an example of an implementation method. MAI informs the driver of a host vehicle (HV) that the other vehicle (OV), i.e. PTW, is nearby even if the driver cannot see the OV.

The evaluation items, methods, and results of the evaluation are described below, and finally the parameter values selected from the results to define the technical description of MAI are described.

2.2.2 Critical time

The “critical time“ is the most important parameter for MAI. This time is calculated by the relative distance and speed between HV and OV shown in the formula below.

$$critical\ time\ [s] = \frac{d}{\Delta d/\Delta t} \qquad d: Relative\ distance\ between\ vehicles \quad \Delta d/\Delta t: Relative\ speed\ between\ vehicles$$

The critical time is not a time until the HV collides with the OV, but a time within which information shall be provided to the driver of the HV. This parameter should be set to an appropriate time which does not interfere excessively with the driver's judgment process to cross an intersection.

2.2.2.1 Evaluation method

The evaluation was done based on two scenarios: 'Crossing at an intersection' and 'Left turn at an intersection'. Figure 1 shows the scenario of crossing at an intersection.

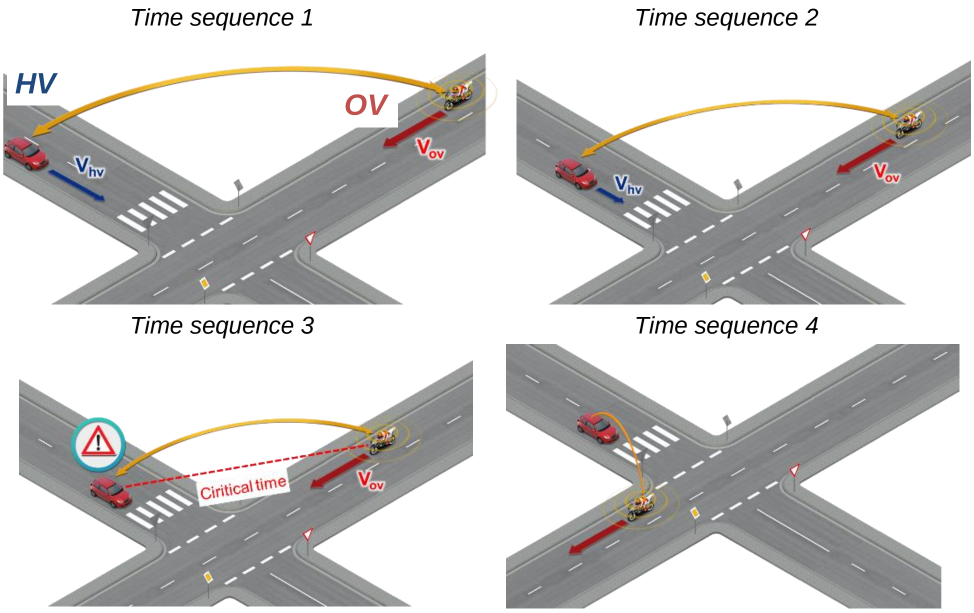


Figure 1: Evaluation scenario of crossing at an intersection

The sequence of this scenario is as follows:

1. The OV which has the right of way and HV are approaching an intersection.
2. The HV starts deceleration to stop at the intersection.
3. The HV receives MAI from on-board HMI during deceleration when OV enters a point at a defined distance that is calculated based on relative speed and critical time.
4. MAI is cleared after the OV has passed in front of the HV.

Figure 2 shows the overview of the other scenario, that is left turn at an intersection, which follows the same sequence of the crossing scenario. These scenarios were evaluated by changing the speed and the critical time as shown in Table 1.

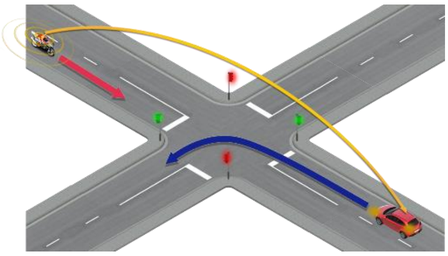


Figure 2: Overview of left turn scenario

Table 1: Parameter to evaluate the critical time

Scenario	HV Speed [km/h]	OV speed [km/h]	Time to evaluate [sec]
Crossing	30	40 or 80	4, 5, 6 or 7
Left turn	30	40 or 80	4, 5, 6 or 7

The critical time came from a general participant study and is the result of statistical analysis of the time, which car (HV) drivers (test subjects) judge to be acceptable. The actual evaluation scenes of the tests are shown below in Figure 3.

Figure 3: Evaluation scenes for critical time evaluation

2.2.2.2 Evaluation results

As stated above, the evaluation test was conducted for the two scenarios with two speeds as a factor of the critical time. With N = 6 drivers performing all variations, the total number of measurements was 96 (6 drivers * 2 scenarios * 1 HV speed *2 OV speeds * 4 Critical times * 1 trial). The results are shown below as histogram in Figure 4. For each factor, these show the critical times that were judged to be acceptable by the drivers.

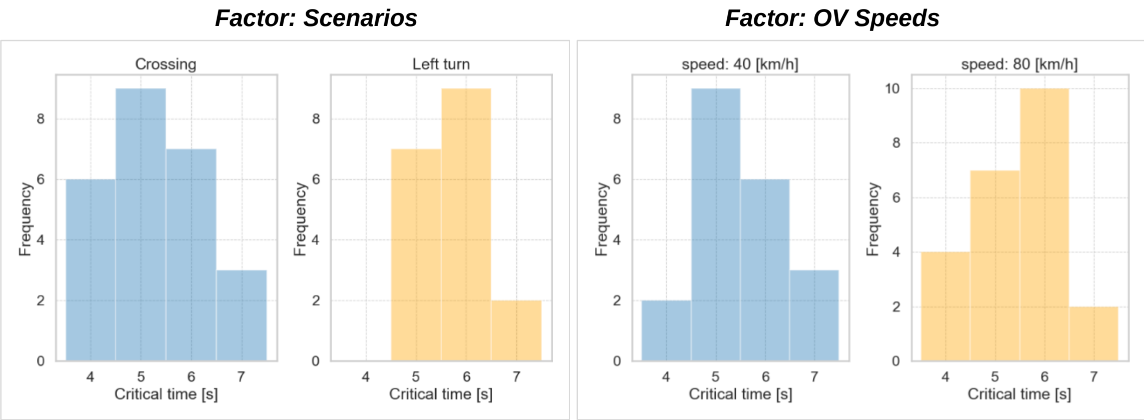


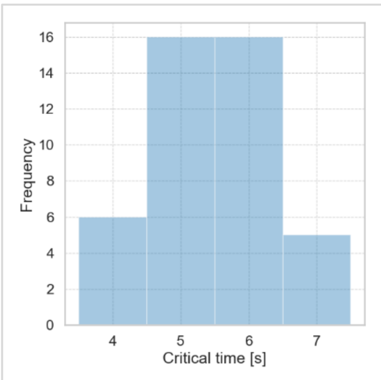
Figure 4: Number of drivers judged as acceptable by each factor

Then Welch's t-test was applied to determine whether the above two factors affect the critical time. The results are shown in Table 2.

Table 2: The result of the Welch's t-test

Data sets by factors	Groups	Measurements	Mean	SD	Welch's t-test	Effect size
Scenarios	Crossing	48	5.28	0.98	t = -1.802 P = 0.075	d = 0.527
	Left turn	48	5.72	0.67		
OV speeds	40 km/h	48	5.50	0.89	t = -0.409, P = 0.683	d = 0.073
	80 km/h	48	5.43	0.90		

Since both P-values are more than 0.05, they do not have a statistically significant difference. Therefore, these factors should be judged as not affecting the critical time. Hence, the results in which drivers judged acceptable are combined into one and shown below as a histogram in Figure 5.



Fundamental statistics
Mean: 5.47
Median: 5.0
Standard: 0.88

Figure 5: Number of drivers judged as acceptable

As this result, it is considered to set the critical time to 5.5 seconds proximate to mean value.

2.2.3 Boundary angle of Ahead area

The “boundary angle of Ahead area” is one of the important parameters for MAI. It determines the range of the Ahead area, which is one of the four areas classified around the HV, as shown in Figure 6. If the boundary angle is not defined as a relevant value, it increases the possibility of collision because drivers may feel anxious and will not be able confirm the relevant direction of the approaching vehicle.

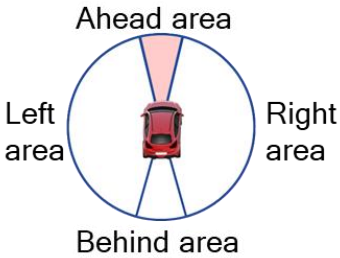


Figure 6: Image of four classified areas

2.2.3.1 Evaluation method

Figure 7 with its sequences show the scenario to evaluate the boundary angle of Ahead area.

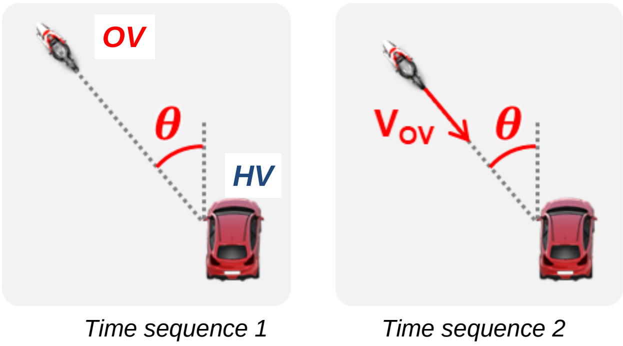


Figure 7: Evaluation scenario

The sequence of this scenario is as follows:

1. The HV and the OV are placed at a defined angle as viewed from HV’s driver position.
2. The OV rider approaches the HV and maintains the set angle. The HV driver judges the direction of OV whether it is coming from ahead of the HV or from the left side of the HV.

This scenario was evaluated by changing the approaching angle of OV as shown in Table 3.

Table 3: Parameter to evaluate the boundary angle of ahead area

HV Speed [km/h]	OV speed [km/h]	Approaching angle [deg]
Stationary	40	10, 15, 20, 25, 30, 35 or 40

Sensory evaluation testing, followed by statistical analysis, was performed to be able to determine the correct boundary angle of the ahead area. The drivers of the HV are tasked to judge the oncoming direction of the OV from various angles and comment whether the OV is coming from ahead, from the left or (if they cannot judge) from a grey area. The actual evaluation scene of the test is shown below in Figure 8.

Figure 8: Evaluation scene for boundary angle of Ahead area

2.2.3.2 Evaluation result

As stated above, the evaluation test was conducted with 7 drivers to evaluate the direction for the approaching vehicle. Since the test results depend on human sensibilities, the results were calculated by a method of constant stimuli based on psychophysics. The number of drivers who judge the direction of the oncoming OV as from ahead, left or grey area is counted and shown below in Figure 9 and Figure 10 as histograms.

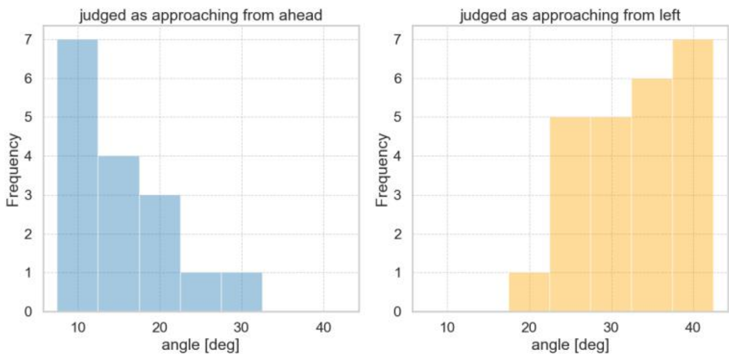
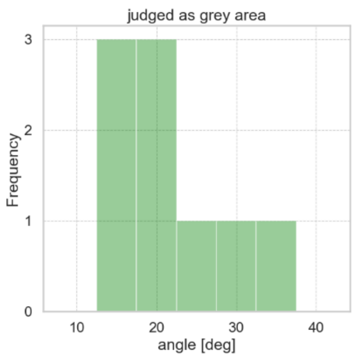


Figure 9: Number of drivers judged as approaching from ahead or from left



Fundamental statistics
Mean: 21.67
Median: 20
Standard: 7.07

Figure 10: Number of drivers judged as grey area (unable to distinguish)

From the result in Figure 10, it is considered appropriate to set the boundary angle of ahead area to 20 degrees, which is approximately the mean value of the grey area.

2.2.4 Time to clear MAI notification

The "Time to clear the MAI notification" is one of the important parameters for MAI. This parameter is defined as the time duration from the moment when the OV passes the HV until when MAI (which is displayed on the HMI of the HV) is cleared. If the MAI notification on the HMI is displayed for excessive amount of time after the OV passes, there is a risk that the HV driver will experience this as an annoyance. It is therefore necessary to define an appropriate time for this parameter.

2.2.4.1 Evaluation method

Figure 11 with its sequences shows the scenario that was used to evaluate the time to clear MAI notification.

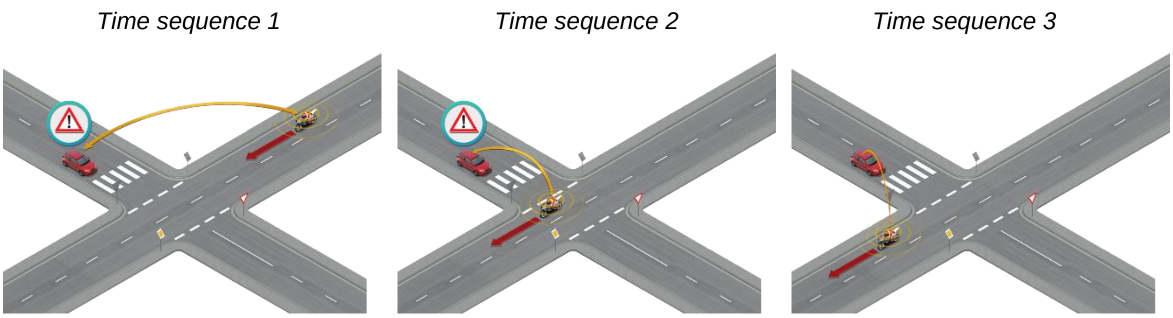


Figure 11: Evaluation scenario

The sequence of this scenario is as follows:

1. The HV remains stationary at an intersection, and MAI notification is displayed on its HMI to inform the presence of the nearby OV.
2. The OV passes in front of the HV.
3. MAI on the HV's HMI is cleared automatically after the defined time duration from time sequence 2.

The time to clear the MAI notification was evaluated in this scenario as shown in Table 4.

Table 4: Parameter to evaluate the time to clear MAI displayed

HV Speed [km/h]	OV speed [km/h]	Time to clear the MAI notification [sec]
Stationary	40	0, 1, 2 or 3

The time to clear the MAI notification is determined by a statistical analysis of the time derived from sensory evaluation tests in which car drivers make a judgement of acceptability in respect of the time the MAI notification is being displayed. The actual evaluation scene is shown below in Figure 12.

Figure 12: Evaluation scene

2.2.4.2 Evaluation result

As stated above, the evaluation test was conducted with 6 drivers to evaluate the time to clear MAI notification. The total of measurements was 48 (6 drivers * 1 OV speed * 4 time duration * 2 trials) and shown below in Figure 13 as histogram.

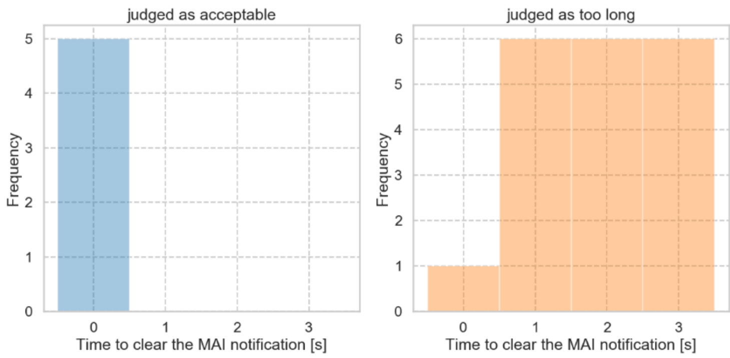


Figure 13: Number of drivers judged as acceptable or too long

From these results, we can conclude that almost every driver considered that MAI notification was displayed too long if it remained on the HMI after the OV had passed. Therefore, it is considered appropriate to set the time to clear the MAI notification at 0 seconds, i.e. immediately after the OV has passed.

2.2.5 Discussion and future development of MAI

In this evaluation test, the test subjects were from CMC having been familiar with the test car. There is a possibility that the test results could be different in case they would be obtained from subjects coming from the general public. In addition, the number of test subjects is small, and it cannot be stated that an effective statistical analysis has been implemented.
Evaluation of the critical time, which is the most important parameter for MAI, with statistically appropriate number of samples should be considered.

2.3 EEBL

The EEBL (Electronic Emergency Brake Light) is an application to broadcast its own emergency braking situation to surrounding vehicles, including those that have their line of sight obstructed by other vehicles or bad weather like fog or rain. This application drastically reduces the delay in reaction time by subsequent vehicles. PTW can perform both transmit and receive EEBL message. Here, the evaluation item, the evaluation method, the evaluation result, and finally the parameter value selected from the result to define the technical description of EEBL are described.

2.3.1 Time to clear EEBL notification

The time to clear EEBL notification is a parameter for the EEBL application. It is defined as the time to clear the EEBL notification on the HMI after the host vehicle (HV) stops behind the other vehicle (OV) (here in after referred to as "stop pattern") or the HV passes the OV (here in after referred to as "pass pattern").

2.3.1.1 Evaluation scenario

This 'time to clear' is determined by sensory evaluation tests: statistically analysing the time which subjects riding the HV judge to be acceptable. Two PTWs equipped with C-ITS devices are used in this evaluation. The evaluation scene is shown below.

Figure 14: Evaluation scene to clear EEBL notification

This application assumes that two vehicles are traveling in the same lane or close together. However, two PTWs run adjacent lanes in this test for the safety of testing.

2.3.1.1.1 Evaluation scenario: Stop pattern

The sequence of this scenario is as follows:

1. The HV and the OV run at a constant speed (70 km/h). Then, the OV decelerates (deceleration < -7 m/s^2). The OV sends a DENM.
2. The HV receives the DENM and displays the EEBL notification on its HMI. The HV rider starts deceleration and stops behind the OV.
3. The EEBL notification on the HV's HMI is cleared automatically after the defined time period.

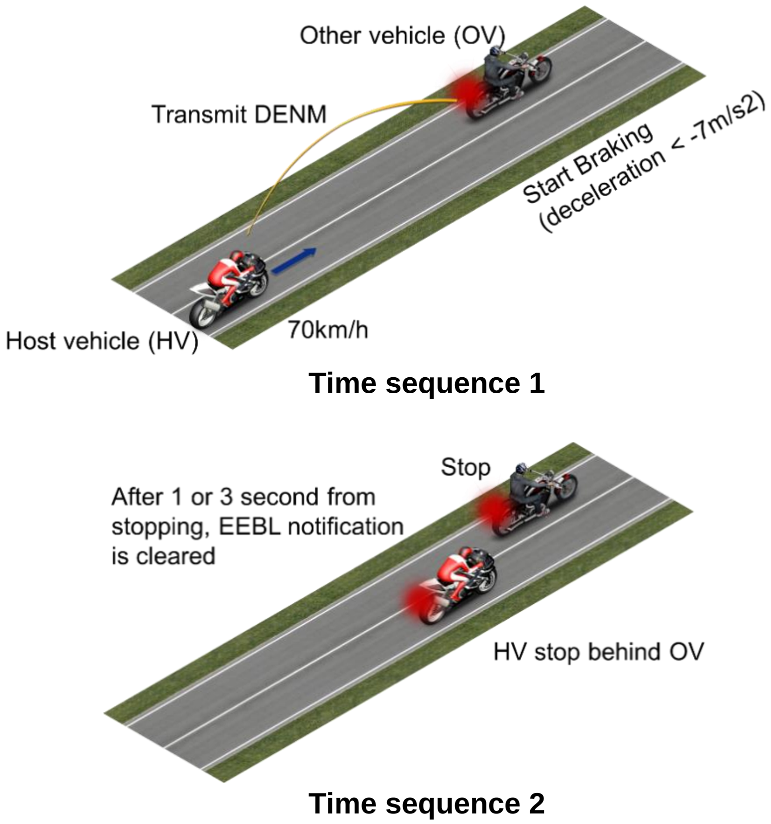


Figure 15: Evaluation scenario of stop pattern

This time to clear the EEBL notification was evaluated in this scenario as shown in Table 5.

Table 5: Parameter to evaluate time to clear EEBL notification

Initial Speed [km/h]	***Behavior of HV***	***Time to clear [sec]***
70	*stop behind the OV*	*1 or 3*

The appropriate time to clear EEBL notification is determined by a statistical analysis of sensory evaluation tests, in which riding subjects are asked to judge the acceptability of the time to clear.

2.3.1.1.2 Evaluation scenario: Pass pattern

The sequence of this scenario is as follows:

1. The HV and the OV run at a constant speed (70 km/h). The OV decelerates (deceleration < -7 m/s^2). The OV sends a DENM.
2. The HV receives the DENM and displays the EEBL notification on the HMI. The HV rider starts deceleration and passes the OV.
3. The EEBL notification on the HV’s HMI is cleared automatically after the defined time period.

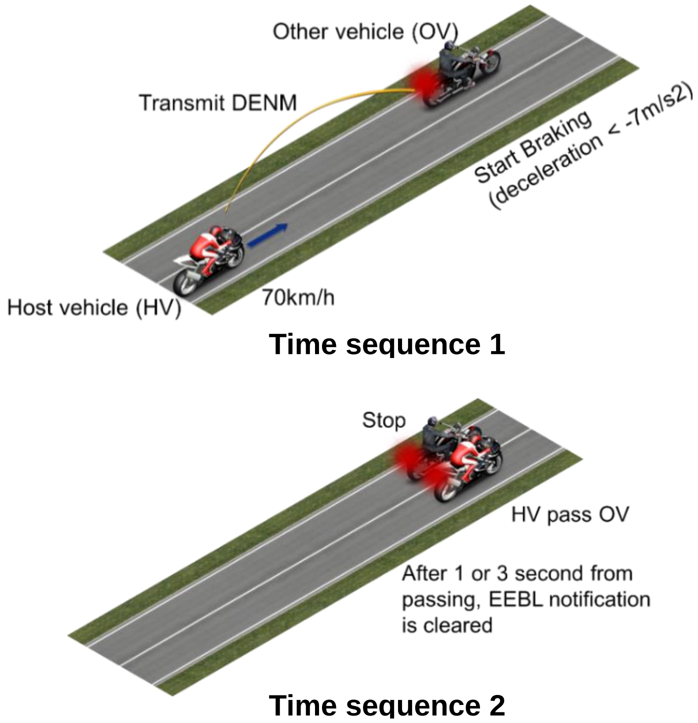


Figure 16: Evaluation scenario of pass pattern

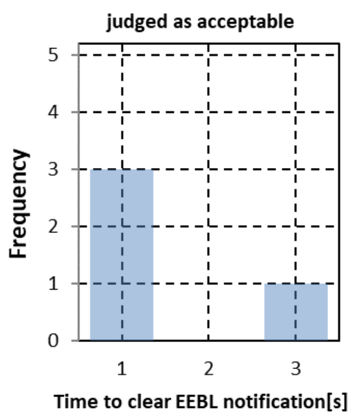
The time to clear the EEBL notification was evaluated in this scenario as shown in Table 6.

Table 6: Parameter to evaluate time to clear EEBL notification

Initial Speed [km/h]	***Behavior of HV***	***Time to clear [sec]***
70	*pass the OV*	*1 or 3*

2.3.1.2 Evaluation result

2.3.1.2.1 Evaluation result: Stop pattern



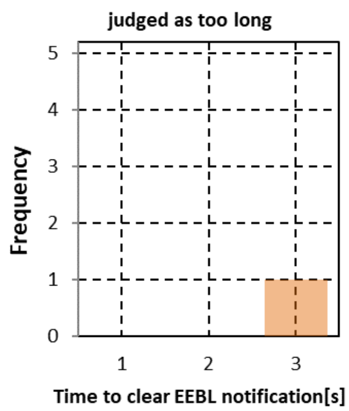


Figure 17: Histogram judged as acceptable *Figure 18: Histogram judged as too long*

From the above pilot test, it seems that the EEBL notification is displayed too long if it remains on the HMI after stopping behind the target vehicle.

2.3.1.2.2 Evaluation result: Pass pattern

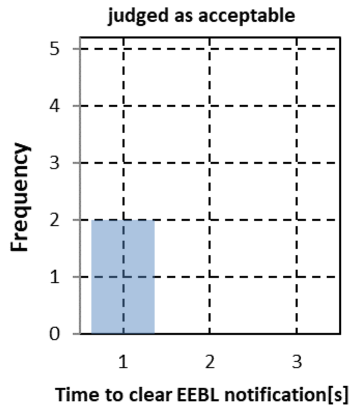


Figure 19: Histogram judged as acceptable

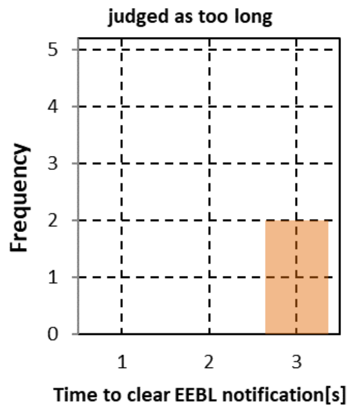


Figure 20: Histogram judged as too long

From the above pilot result, it seems that the EEBL notification is displayed too long if it remains on the HMI after passing the target vehicle.

In this evaluation test, the number of test subjects is too small, and it cannot be stated that an effective statistical analysis has been implemented. However, it seems desirable to clear a notification shortly after the critical situation is over in general.

3 Evaluation of System

3.1 Antenna measurements on PTW

3.1.1 Objective

Usually the horizontal antenna pattern of a car is nearly circular with constant gain to each direction. For PTWs it seemed unclear if it could result in a similar pattern due to different size and shape of the vehicle itself. The purpose of the antenna measurements was to gain experience where appropriate positions can be located, how a radiation pattern would look like and which impact does the human body or roll angle have.

3.1.2 Radiation pattern of the dipole antenna

Reflections, due to the PTW itself, are not easy to predict and may, in some directions, enhance or degrade the radiation patterns as indicated in Figure 21. The picture shows a comparison between an ideal round pattern with no gain (black line), a measurement of a standalone dipole antenna in an anechoic chamber (red line), the same dipole antenna in a radome mounted on front (yellow line) and on the rear of a PTW (blue line). In that case, a KTM 1290 Super Duke GT was considered to represent the PTWs.

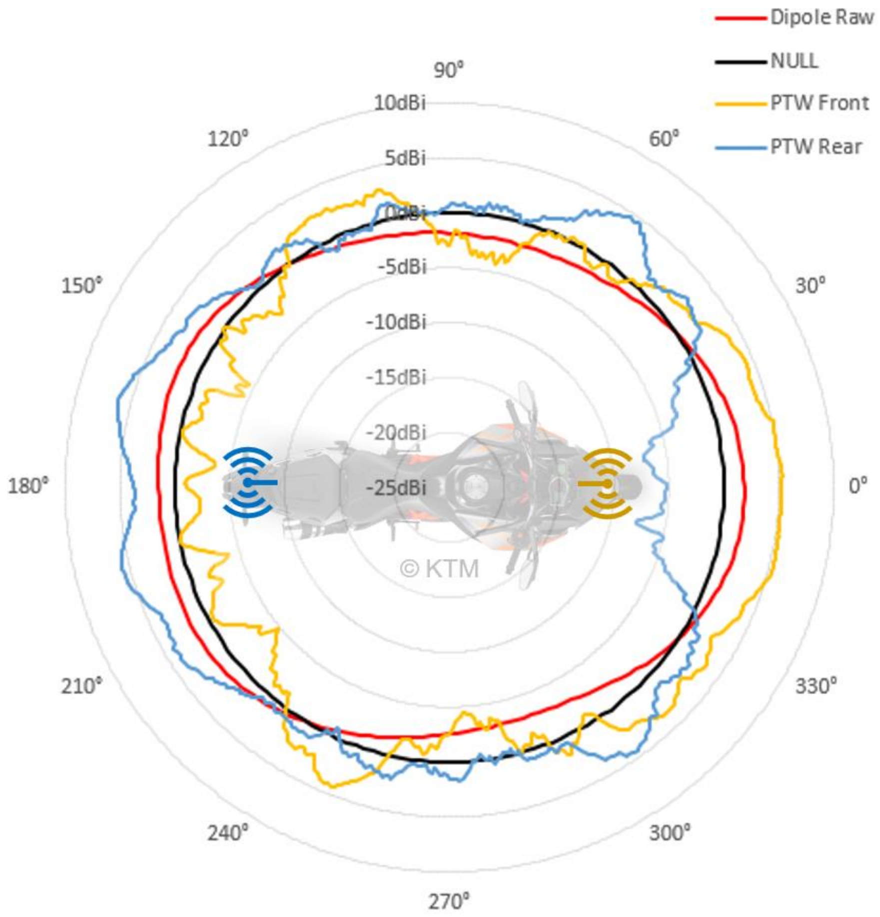


Figure 21: Comparison Dipole Raw (red), omnidirectional zero gain (black), PTW Front (yellow) and PTW Rear (blue)

3.1.3 Antenna diversity

The following antenna pattern was measured on a PTW equipped with one antenna in the front and one in the rear, as seen as single measurements in the previous chapter 3.1.2. Using antenna diversity (green line) showed significant improvement achieving an omnidirectional radiation pattern (black line).

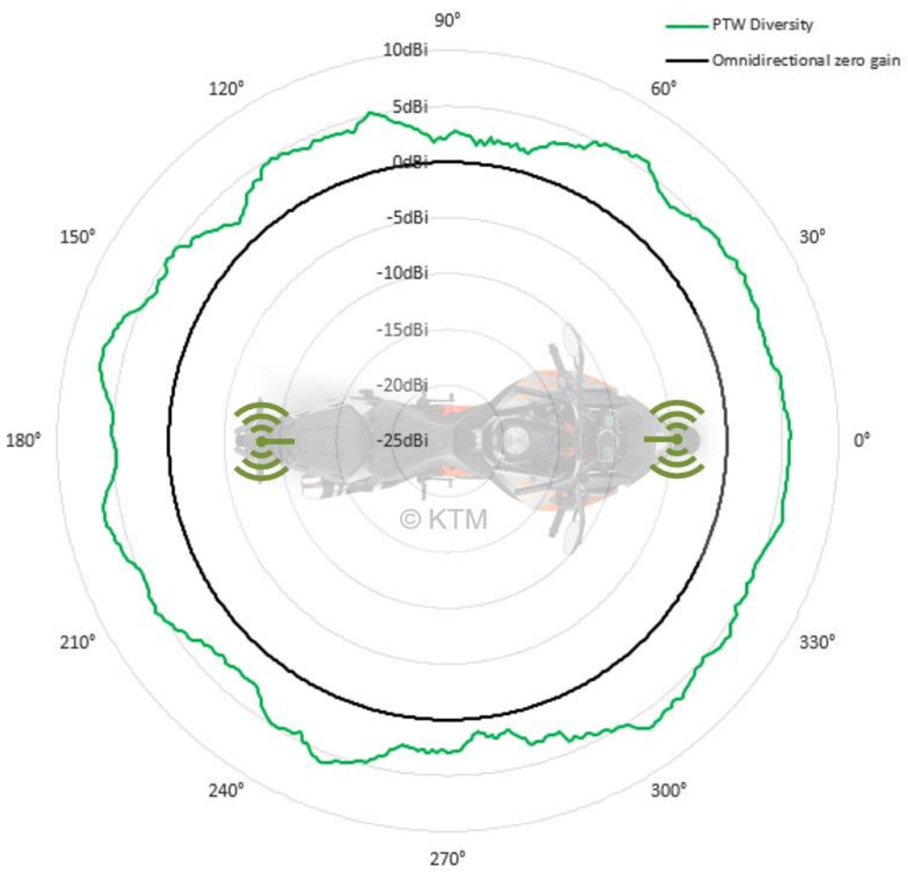


Figure 22: Omnidirectional zero gain pattern (black) compared to a measured diversity antenna pattern (green)

3.1.4 Different PTW types impacting antenna performance

Different types of PTW implicate different antenna patterns, therefore PTW antenna patterns cannot be generalized as shown in Figure 23. Those measurements were done in a radome with the antennas mounted on its front section. The one monopole antenna was mounted on a scooter (black line), the two dipole antennas on a sport PTW (green line) and a naked sport touring PTW (orange line). The mounting positions on the different vehicles are shown in Figure 24. The vehicle size, shape and material impact the resulting pattern in each direction as shown in Figure 23.

For those measurements a Honda PCX representing scooters, a Kawasaki Z1000SX representing sportbikes and a KTM 1290 Super Duke GT representing naked bikes were considered.

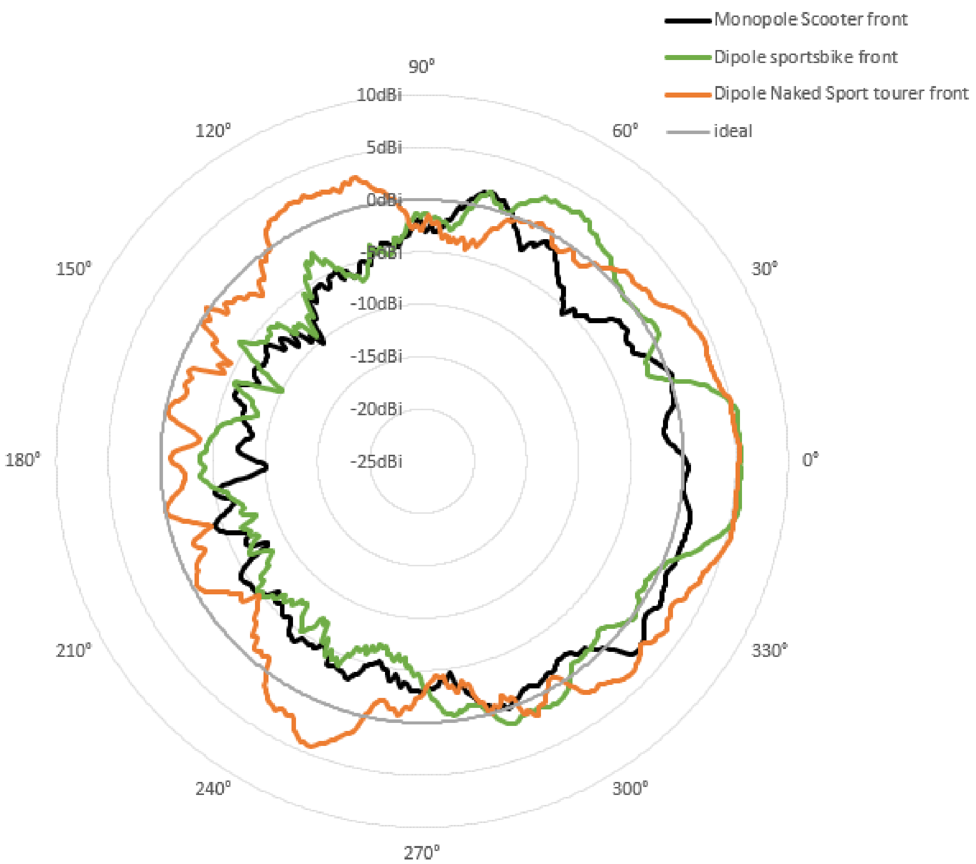


Figure 23: Comparison of different PTW types. Scooter (orange), Sportbike (green), Naked sports tourer (orange)

Scooter Sportbike Naked sport tourer

Figure 24: Mounting position of the antennas.

3.1.5 Impact of a human body to the radiation pattern

Looking at the mounting positions in the front and rear of the PTW, it was expected that the human body of rider and pillion might have strong impact to the radiation pattern. Therefore, the measurement “PTW front” of chapter 3.1.2 was repeated, with a human body sitting on top.

Figure 25: Measurement set-up with a rider in the radome

The actual measurement results nevertheless indicated a minor impact (Figure 26). The human body (black line) seems to act as an absorber and reduces the overall gain. The average gain is about 0.5 dB lower compared to the measurement without rider (yellow line). Due to this result there were no further measurements with a pillion and luggage proceeded.

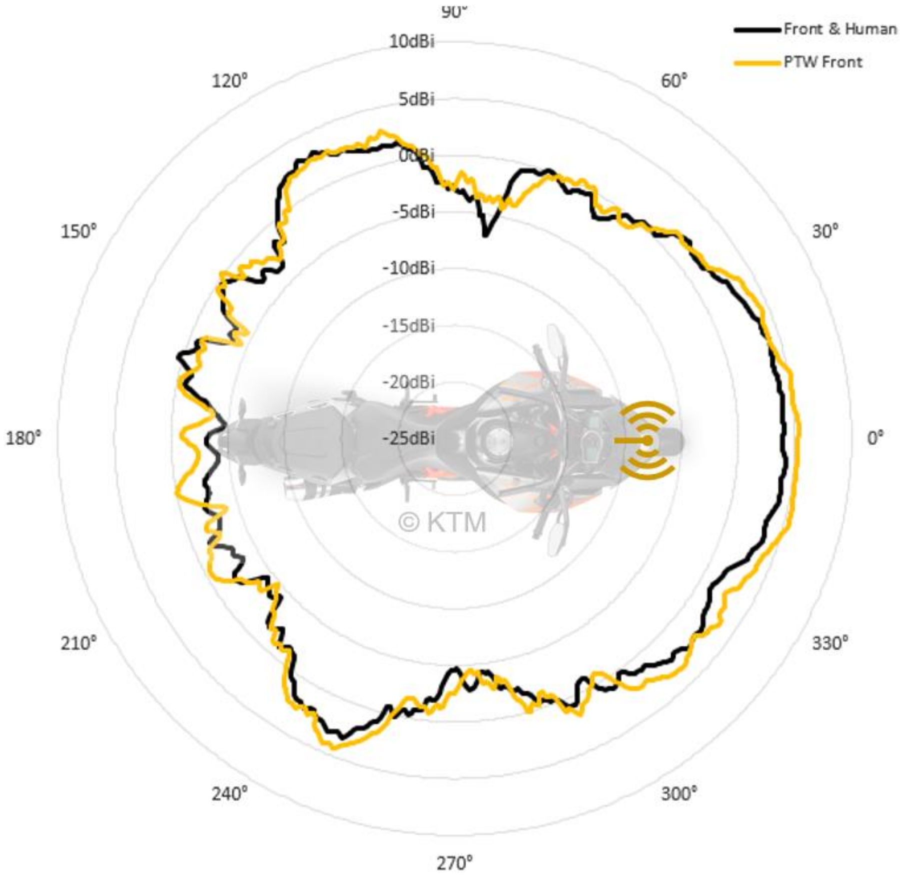


Figure 26: Impact of a human rider

3.1.6 Impact of a Roll angle to the radiation pattern

Roll angle is another PTW specific parameter which was thought to influence the antenna radiation pattern. The measurement was executed with a PTW in a 30° lean angle utilizing the front antenna as seen in Figure 27.

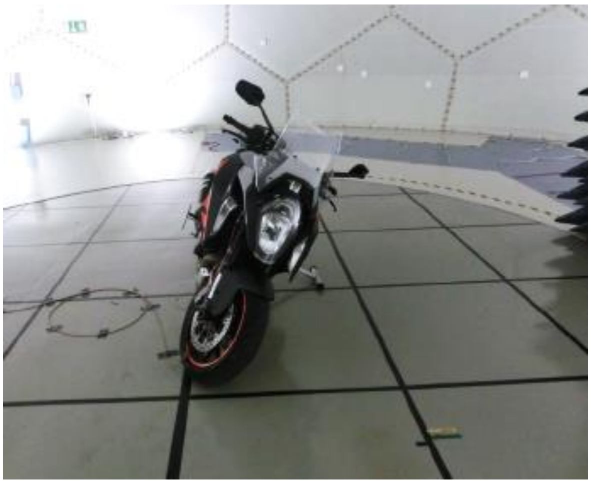


Figure 27: Roll angle measurement conditions at the radome

The measurement result is shown in Figure 28. As from the figure, the impact of the roll angle was less than expected and a slight shift to the leaning direction was observed (black line) compared to the measurement "PTW front" of chapter 3.1.2 (yellow line).

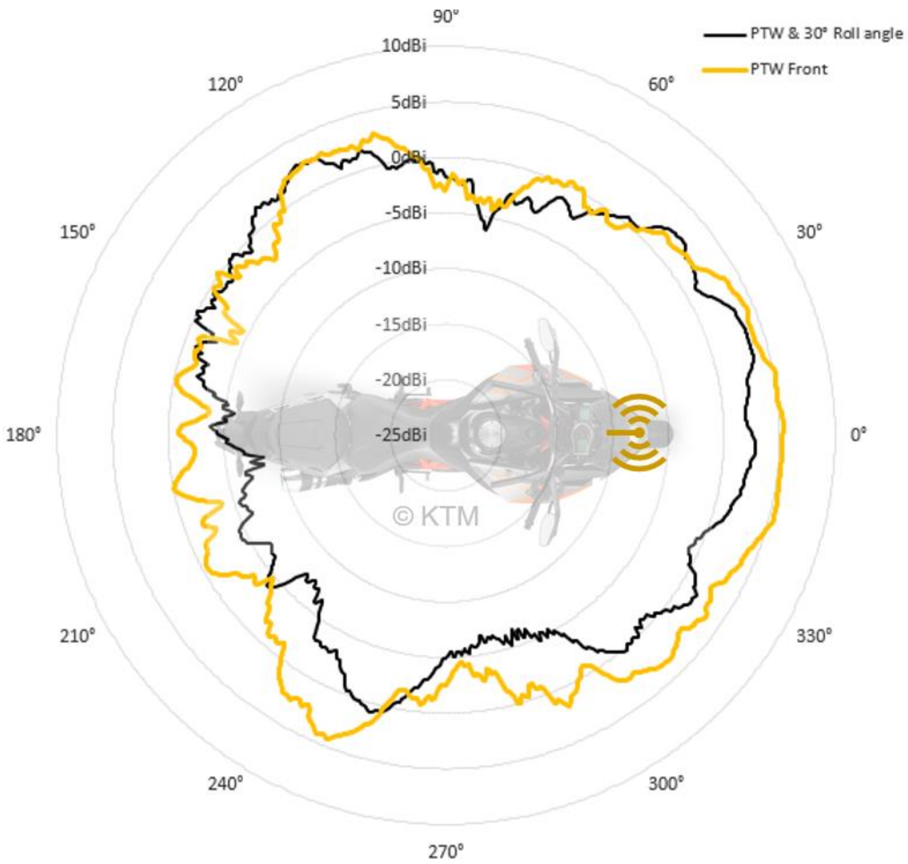


Figure 28: Influence due to leaning 30° to the left

3.1.7 Conclusion of antenna measurements

A reasonable communication distance might be met already using one antenna mounted either in the front or the rear part of a PTW, this has to be analysed individually.
Nevertheless, Figure 29 illustrates the benefits of using antenna diversity compared to just one antenna.

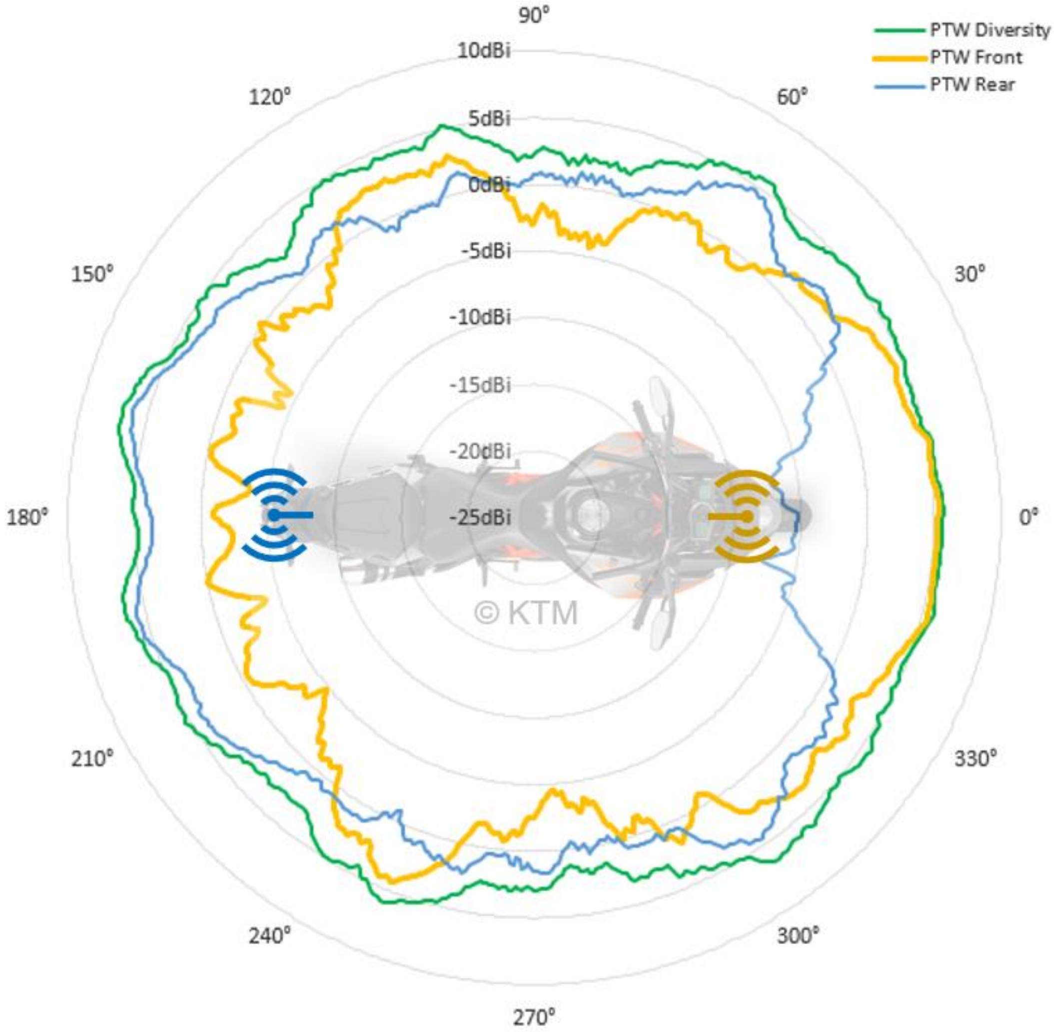


Figure 29: Different mounting positions (yellow, front) (blue, rear) compared diversity (green)

In diversity mode, using two antennas, it is possible to reach a comparable performance to a car with a roof mounted antenna. For the impact on absorption by the rider and the roll angle, it was found that both do not significantly affect the overall performance of the antenna radiation pattern.

3.2 Dynamic antenna measurements

In addition to the static measurements, dynamic measurements were performed. The purpose of these measurements was to validate that the results of the static antenna measurements would be applicable for the communication system.

3.2.1 Basic settings of the V2X Units

- Carrier Frequency: 5880 MHz
- Bandwidth: 10 MHz
- Data Rate: 6 Mbps
- Packet size: 1000 Bytes (CAM ~400-800 Bytes)
- Transmit interval: 50 ms (CAM 100 ms < x < 1 s)
- Output power: 23 dBm
- Antenna installation: As described per test (Front / Rear / Diversity)

3.2.2 Measurement criteria

PER (Packet Error Rate) of 10% is considered as good quality.
PER (Packet Error Rate) of 10% to 20% is considered as medium quality.
PER (Packet Error Rate) of more than 20% is considered as signal loss and is the crucial factor determining the range.
Figure 30 is an example of the measurement and an explanation how the measurements were performed. The receiver is mounted at a tripod and located stable at one position of the road. The sender is installed at the PTW and movable. The maximum distance of the PTW and the receiver was approximately 700 m. The PER rises at the distance of ~300 m and reaches 20% at about 420 m. That's where the signal loss is stated. After turning, the PER passes again the < 20% value at about 600 m.
Due to reflections of other road participants, the PER value rises from time to time with no involvement of the transmitter or receiver.

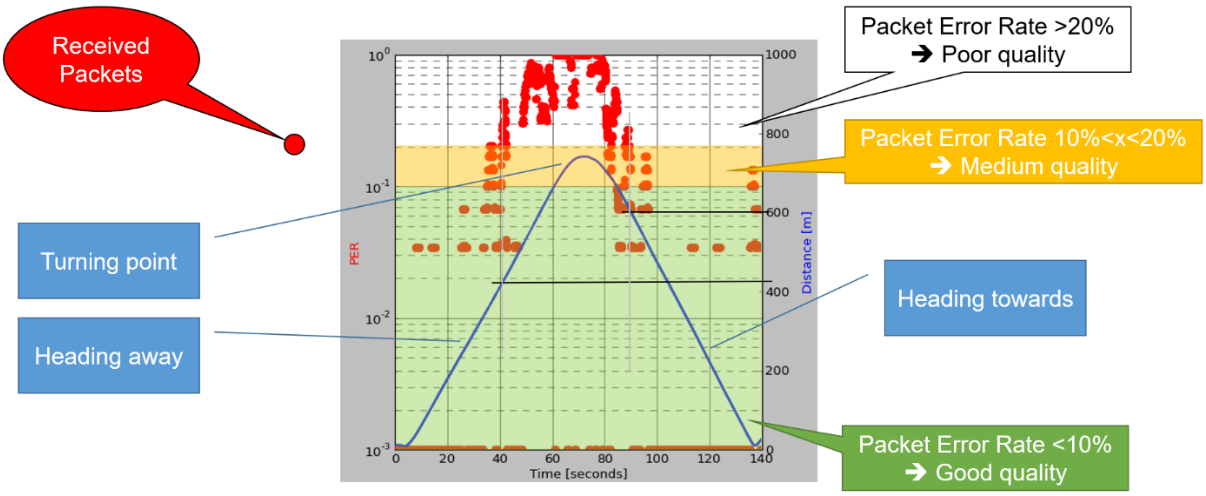


Figure 30: Example of dynamic measurement

3.2.3 Basic measurement

The PTW (Tx) is moving and the Receiver stable, distances between 380 m (front antenna only, backwards) to 700 m (diversity, front and backward) were achievable. Since 700 m was the turning point during the test, it is likely that a range greater than 700 m is achievable using a diversity of both antennas.

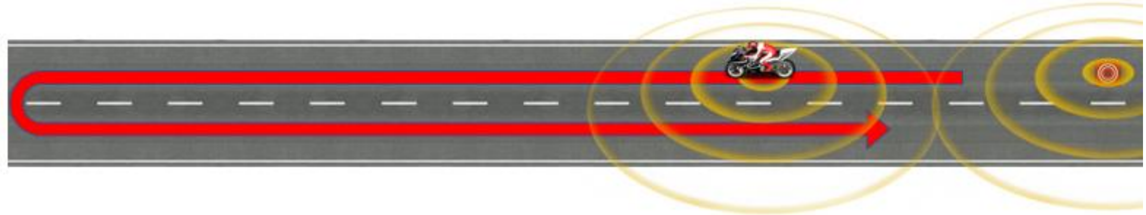


Figure 31: Visualization of a basic measurement

3.2.4 Basic EEBL Scenario

The PTW (Tx) is moving, the Receiver stable and a car is parked in between functioning as blockage. A distance between 210 m (front antenna only, backwards) to 620 m (diversity, front- and backwards) was achievable.

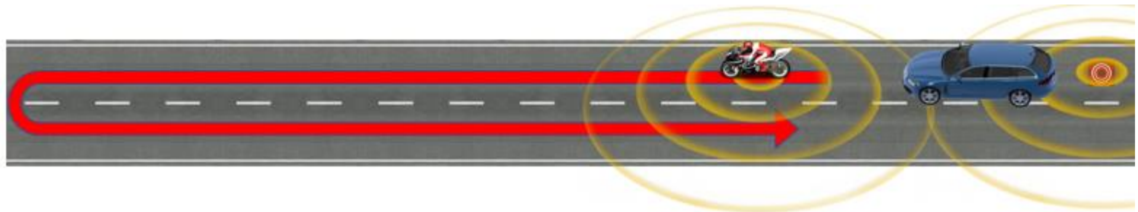


Figure 32: Visualization of a basic EEBL measurement

3.2.5 Advanced EEBL Scenario

The PTW (Tx) is moving, the Receiver stable and two cars are parked in between functioning as blockage. A distance between 280 m (front antenna, backwards) to 500 m (diversity, front- and backwards) was achievable.

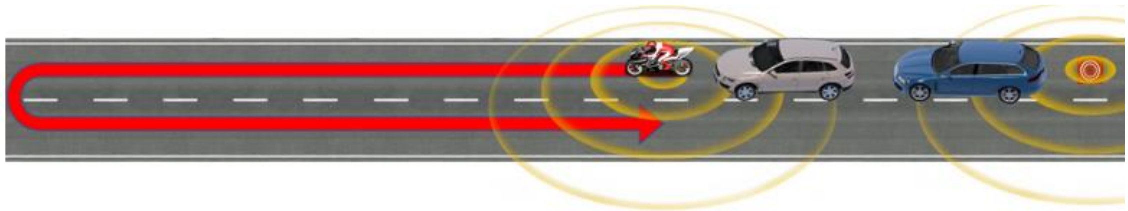


Figure 33: Visualization of an advanced EEBL measurement

3.2.6 Intersection Scenario 1 and 2

No limitation to the application was found during the tests under optimal sky conditions, a free parking lot in a rural area within a range of 200 m.

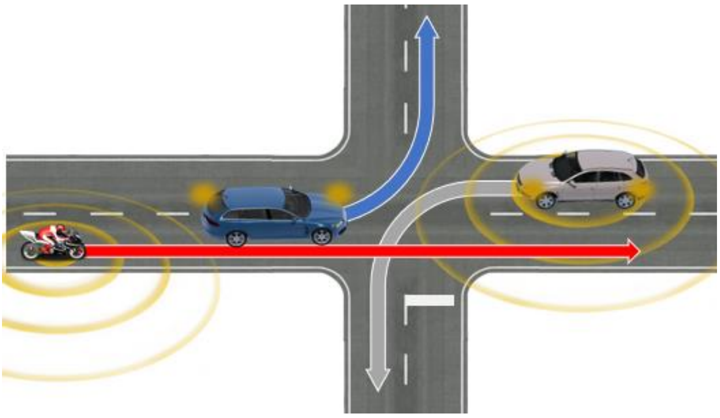


Figure 34: Visualization of LTA Scenario, both cars turning

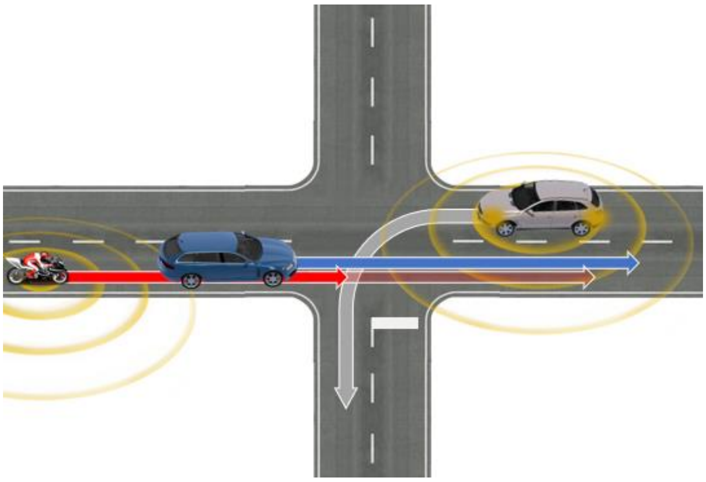


Figure 35: Visualization of LTA Scenario, one car turning

3.2.7 Conclusion

Over 700 m communication range were established under optimal line-of-sight conditions during the tests.

In No-line-of-sight scenarios, for example in cities, a communication range of approximately 150 m was achieved. Buildings in a city and other vehicles act as reflectors improving the communication performance. Wooden areas, playgrounds or grasslands show absorbing effects.

In general, reflections improve the system communication performance in urban areas with buildings between the communicating vehicles.

'Rear antenna only' measurements resulted in poor performance in static measurements and hence it is not recommended to use a 'rear antenna only' solution.

3.3 Localisation

3.3.1 Objective

The localisation system outputs the geographical positioning information by calculation using GNSS, IMU data and odometry. The position estimation is challenging when the system has poor satellite signal. In this case, the position is usually calculated based on the last information obtained by GNSS and the IMU data. However, it is of common knowledge that PTWs have a different dynamics with respect to cars and trucks. Because of that fact an evaluation of PTW dynamics deemed necessary.
Therefore, CMC evaluated the regular driving dynamics of PTW, verifying position, speed and heading accuracy, and compared to C2C-CC definition. The localisation system developed by CMC (hereinafter called "Localisation System") for this evaluation purpose has several levels of calculation method based on the information used for the position estimation, for example stand-alone GNSS or fusion of GNSS and IMU data. CMC validated which level of specification shall be observed to meet the C2C-CC requirements for the localisation. To account for inevitable degradation of the position estimation due to the satellite environment, required confidence values are defined for different scenarios. In the case of all scenarios defined by C2C-CC[1], the antenna position reported by the Localisation System is compared with the ground truth data measured by the independent system, OXTS RT3003. In this test, u-blox M8U, the positioning module, is also evaluated as the test system.

3.3.2 Test setup

The setup of test vehicle is explained in this chapter. Figure 36 shows the position of antenna for each Localisation System. The antenna of the Localisation System and that of the ground truth system are installed on the passenger seat. The u-blox M8U is installed in the right pannier case. As antennas are installed next to each other, no correction is applied for the offset to calculate the position error. Note, that the reference point[2] for the C-ITS system is the position at the front of vehicle.

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[1] CAR 2 CAR Communication Consortium, *Basic System Profile V1.4.0* (https://www.car-2-car.org/documents/basic-system-profile/, accessed on 06.11.2020)
[2] ETSI EN 302 637-2 V1.4.1 (2019-04) (https://www.etsi.org/deliver/etsi_EN/302600_302699/30263702/01.04.01_30/en_30263702v010401v.pdf, accessed on 06.11.2020)

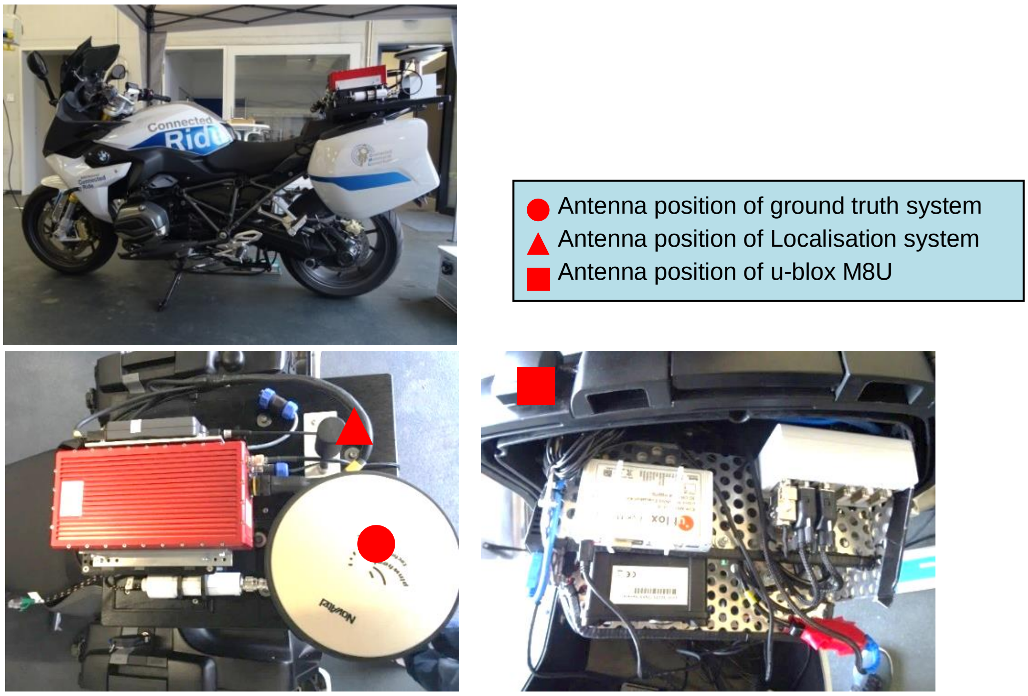


Figure 36: Test vehicle (top), Top view (left), Right pannier case (right)

Figure 37 shows the test system environment for each Localisation System. Localisation System consists of GNSS receiver and IMU. RT3003 is chosen as ground truth system and u-blox M8U is used as a system currently available in the market. The data recorded by each Localisation System is collected by the Application Unit (AU). (Refer to 3.3.5).

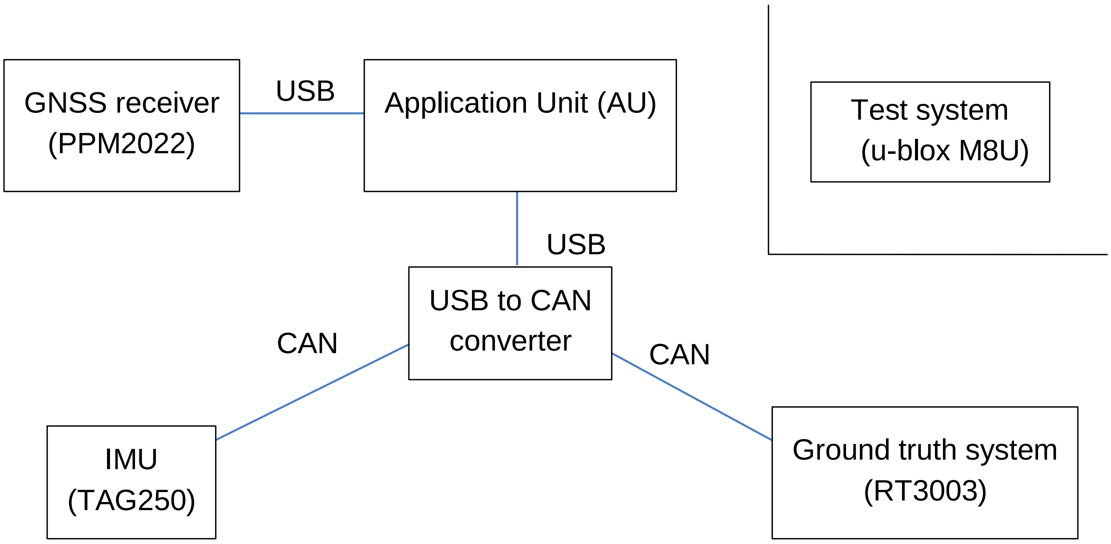


Figure 37: Test system environment

3.3.3 Localisation systems

This section provides an overview of each Localisation System.

3.3.3.1 Ground truth system

When performing evaluation of Localisation System, ground truth must be defined using instruments which are more precise than the system subject for evaluation. CMC has selected OXTS RT3003 as the instrument to define ground truth. This instrument is capable of providing high precision position and vehicle attitude which are often used for testing Advanced Driver Assistance Systems (ADAS) and Automated driving. Also, the performance of RT3003 as the ground truth system is proven by Siemens and confirmed to be equivalent to the test done by C2C-CC.
OXTS RT3003 includes a high precision IMU which is integrated with GNSS position measurement system capable of measuring accuracy in order of centimeters enabling output of high precision vehicle attitudes and position accuracy at high refresh rates.

3.3.3.2 Localisation System

3.3.3.2.1 Calculation software

3.3.3.2.1.1 *Calculation models*

CMC has prepared the following 4 levels of calculation models to investigate the solutions needed to fulfill the C2C-CC requirement. Refer to section 2.1 Localisation in the System Specification document for the detail of the each calculation model.

Level 1 - GNSS positioning
Level 2 - GNSS positioning + GNSS constant-speed and heading
Level 3 - Integrated Navigation Algorithm (GNSS and IMU)
Level 4 - Integrated Navigation Algorithm (GNSS, IMU and Odometry speed)

3.3.3.2.1.2 *Dead Reckoning (DR) sensor fusion algorithms*

DR sensor fusion algorithms adopted in the Level 3 and 4 are explained in this section.
DR sensor fusion outputs position of the moving vehicle by dividing conditions into three functions; attitude, speed and position, and employs independent modular structure which the aforementioned three functions are estimated independently and integrating condition of the vehicle as a result. Each module on its own has optimized estimate function using Unscented Kalman Filter (UKF) which enables optimized estimation of the combination time update and observation update values of vehicle conditions by UKF. Name of the filters and condition variables which each filter tracks are as follows;

1. Attitude Filter: tracking the PTW’s attitude in terms of yaw, pitch and roll
2. Motion Filter: tracking horizontal and vertical speeds as well as lateral and longitudinal accelerations
3. Position Filter: tracking the global position in terms of longitude, latitude and altitude

These filters are independent from each other but the final goal is to estimate its own position within the WGS84 coordinate with high accuracy and regard its vehicle condition estimated by these filters as time update values and regard its position from GNSS as observation update value together calculating optimized estimated solution of vehicle position. The flow of the calculation is shown in Figure 38.

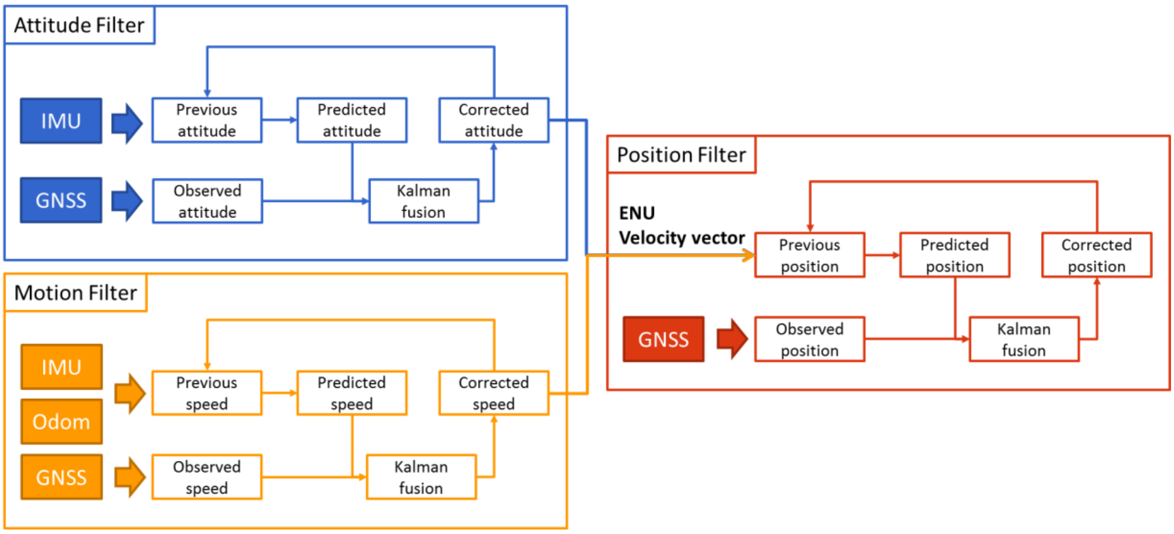


Figure 38: Integrated algorithm flow

As regards to the overall flow of the algorithm, vehicle heading estimated by Attitude filter and vehicle speed towards horizontal direction estimated by Motion filter are combined to calculate speed vector of own vehicle (ENU speed vector) within the East/North/Up coordinate (ENU coordinate) to be input into Position filter. The position information is then estimated inside Position filter. Details of each filter is described in the following section.

Heading of the vehicle in motion is estimated by combining heading angle which is obtained from GNSS as observation update value of the yaw rate on global coordinate system from six axis acceleration and angular velocity measured by the IMU as time refreshed value from attitude filter. Yaw rate in this report is defined as the time difference of yaw attitude on global coordinate system instead of converting into world coordinate system considering angular velocity around vertical axis (Z axis) taking into account attitude angles. This was considered from the viewpoint of accuracy and simplification of the calculation.

For the motion filter, speed values of horizontal and vertical direction are estimated by combining the three axis acceleration measured by the IMU or speed values obtained through vehicle odometry in case of Level 4 as time update values and velocity vector obtained from GNSS as observation update value.

For the Position filter, the location of the vehicle on ENU coordinate is estimated by combining location of the own vehicle obtained from GNSS as observation update value and ENU speed vector. Final output result would therefore be the location of the own vehicle converted from location on ENU coordinates into WGS84 coordinates as longitudes and latitudes on WGS84 coordinates are necessary.

3.3.3.2.2 GNSS receiver (PPM2022)

PPM2022 was used as GNSS for Localisation System calculation. RTCM v2.3 was used as the correction signal, and it was set to the accuracy of DGPS level (PSRDIFF) and measured. The reason for setting the DGPS level is that the RTK is considered to be inappropriate due to the cost when it is considered for future mass-production vehicles.

3.3.3.2.3 Inertial measurement unit (IMU) (TAG250)

TAG250 was installed to estimate the attitude angle (Roll, Pitch, Yaw) of the vehicle needed for Localisation System. TAG250 is a MEMS IMU from Tamagawa Seiki Co. Ltd. which incorporates orthogonal three axis gyroscope and orthogonal three axis accelerometer capable of providing three axis angular velocity and three axis acceleration at a maximum rate of 200 Hz. TAG250 is enabled with leveling calculation which is a feature where it is possible to provide high precision attitude angle of the vehicle by double-signing three axis angular velocity and three axis acceleration.

3.3.3.3 u-blox M8U system

M8U manufactured by u-blox which is a product currently available in the market was evaluated as well. The software in the u-blox M8U corresponds to Localisation System Level 3 solution described above. u-blox M8U is a GNSS receiver module with six axis gyro sensor and accelerometer integrated and adopts Untethered Dead Reckoning (UDR) technology which enables dead reckoning without odometry information such as speed pulses which enables position measurements in situations where wave reception from positioning satellites are difficult such as in Tunnel scenario.

3.3.4 Requirements for Localisation

The tables below show the general requirement and hardware related requirement of C2C-CC regarding localisation.

Table 7: General requirement

Legend
- *✓: Meets requirement of C2C-CC*
- *A: No need to differentiate from car*
- *B: Technically validated*

Requirement	C2C-CC	CMC	Justification
Vehicle states	RS_BSP_190	✓	A
Reference coordinate system	RS_BSP_191	✓	A
Heading	RS_BSP_192	✓	A
ITS-S time	RS_BSP_194	✓	A
Continuation of the vehicle state estimation in case of sensor data unavailability	RS_BSP_195	✓	A
Update frequency of the vehicle state	RS_BSP_197	✓	A
Accuracy estimations	RS_BSP_431	✓	A
Timestamps in messages	RS_BSP_432	✓	A
Difference between station clock and time base	RS_BSP_207	✓	A
Heading report during standstill	RS_BSP_444	✓	A

Table 8: Hardware related requirement

Requirement	C2C-CC	CMC	Justification
Testing of the confidence value	RS_BSP_202	✓	A
Confidence value under optimal GNSS conditions and normal driving dynamics	RS_BSP_205	✓	B
Station clock	RS_BSP_206	✓	A
Regular driving dynamics	RS_BSP_449	Refer to 3.3.7	B
Position confidence	RS_BSP_209	Refer to 3.3.8 Excluded S3(Parking house), S11(Rough road) and S12(Icy road)	B*1
Heading confidence	RS_BSP_209 RS_BSP_457	Refer to 0	B
Speed confidence	RS_BSP_209 RS_BSP_448	Refer to 0	B

***1** CMC shall adopt the definition specified by C2C-CC WG Compliance Assessment. CMC shall follow the test route adopted by C2C-CC as these were already classified in different scenarios.

Table 9: Parameter setting

Parameter	C2C-CC	CMC	Justification
pPotiWindowTime	20-120 s	✓	A
pPotiMaxTimeDiff	20 ms	✓	A
pPotiUpdateRate	10 Hz	✓	A

3.3.5 Data collection

The list of recorded data of the tests is shown in Table 10.
Data used in the Localisation System is collected by AU and stored in one file. The Localisation System is incorporated into AU and provides 4-level geographical positioning information via post-processing.

Table 10: List of data recorded in the test

	Category	Topic	Remark
1	GNSS reciver (PPM2022)	/gnss_info	Including GNSS status
		/gnss_pos	Including latitude, longitude and altitude
		/gnss_time	Including atomic time
		/gnss_vel	Including speed estimated by GNSS
2	IMU(TAG250)	/imu_tag250	Including IMU data
3	Odometry	/vehicledata/odometry	Including vehicle speed
4	Localisation System	/localisation/body	Including vehicle dynamics
		/localisation/info	Including speed and heading
		/localisation/ground	Including yaw, pitch and roll
		/localisation/status	Including algorithm information
		/localisation/ellipsoid_ref	geographical information of reference point
		/localisation/ellipsoid_ant	geographical information of antenna
5	RT3003	Ground truth system	.rd file is also saved in RT3003 itself
		/rt3k/datetime	Including date time
6	u-blox M8U	M8U evaluation kit	.ubx file is also saved in M8U itself

3.3.6 Measurement overview

The evaluation test was conducted for following scenarios. The definition of each scenario is described in 3.3.8.2.

- Open Sky
- Tunnel
- City
- Mild Urban
- Mountain
- Forest
- Half Open Sky

Driving routes identical to C2C-CC were chosen and in total, CMC performed ten data runs. The details of these runs are presented in Table 11. The start and the end location of all

scenarios were defined by C2C-CC. Locations of different scenarios are provided below for Den Haag (Figure 39) and La Roche-en-Ardenne (Figure 40).
Note: Scenarios “Parking house”, “Rough road” and “Icy road” were excluded as it is less common for PTWs.

Table 11: Details of the test runs

Run No.	Date	Location	Scenarios
1	09/09/2019	Den Haag	Open Sky, Tunnel, City, Mild Urban
2	09/09/2019	Den Haag	Half Open Sky
3	10/09/2019	Den Haag	Open Sky, Tunnel, City, Mild Urban
4	10/09/2019	Den Haag	Open Sky, Tunnel, City, Mild Urban
5	10/09/2019	Den Haag	Open Sky, Tunnel, City, Mild Urban
6	10/09/2019	Den Haag	Half Open Sky
7	10/09/2019	Den Haag	Half Open Sky
8	11/09/2019	La Roche-en-Ardenne	Forest, Mountain
9	12/09/2019	La Roche-en-Ardenne	Forest, Mountain
10	13/09/2019	La Roche-en-Ardenne	Forest, Mountain

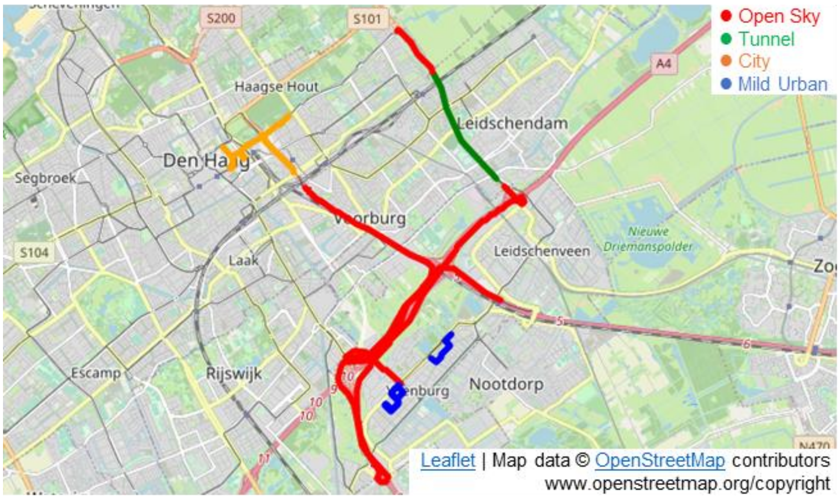


Figure 39: Test course (Den Haag)

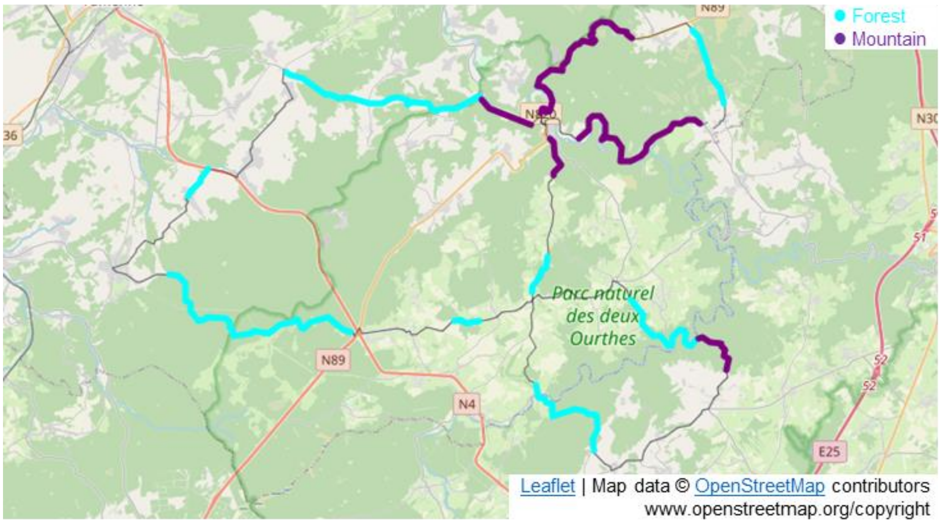


Figure 40: Test course (La Roche-en-Ardenne)

3.3.7 Regular driving dynamics

To verify whether the regular driving dynamics defined by C2C-CC can be applied to PTWs, lateral and longitudinal acceleration and speed of the vehicle obtained from the measurements are evaluated in this section.

3.3.7.1 Data analysis method

Data analysis after recording consists of the following steps (Figure 41):

I. Post-process

II. Cutout - Start and end point of the data for each scenario are matched to C2C-CC.

III. FFT analysis (Sampling frequency = 200 Hz, LPF cut-off frequency = 3 Hz)

IV. Results - Read peak values from all FFT analysis results. Assuming that the peak value is normally distributed for each test scenario, the average value + 3σ is obtained from the average value and the standard deviation σ obtained for each scenario. However, for scenarios whose standard deviation σ of 0.4 or higher and data with large variations are excluded.

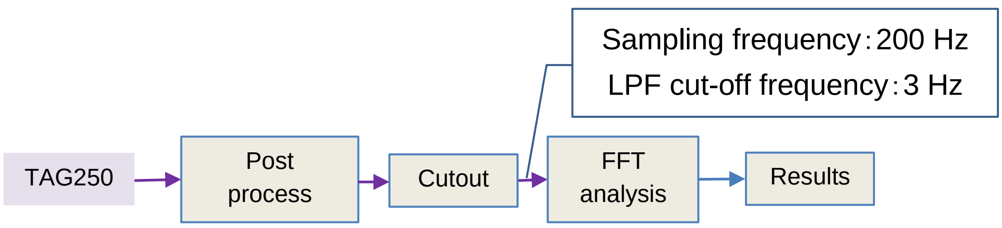


Figure 41: Analysis procedure

3.3.7.2 Measuring direction of acceleration

The axis of acceleration measurement is shown in the Figure 42.

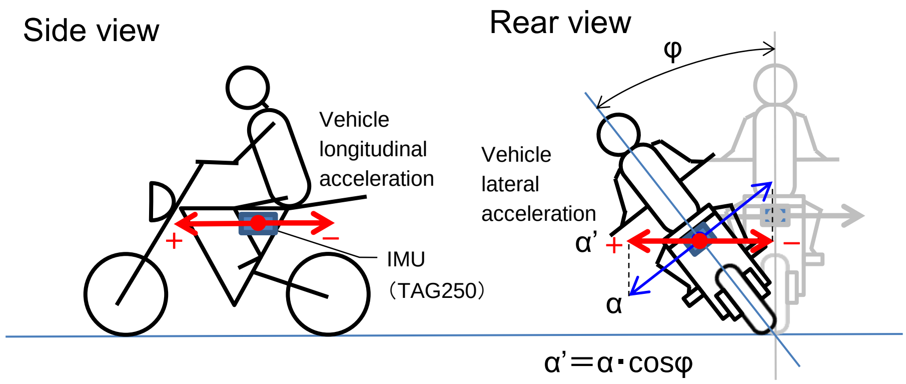


Figure 42: Axis of acceleration measurement

3.3.7.3 Test result of vehicle lateral and longitudinal acceleration

The description of test results for vehicle lateral and longitudinal acceleration is explained in the following section. Maximum lateral acceleration is 1.7 m/s^2 in City scenario, maximum longitudinal acceleration in deceleration direction is 6.0 m/s^2 and maximum longitudinal acceleration in acceleration direction is 5.5 m/s^2 in Mild Urban scenario.

Table 12: Results of vehicle lateral Acceleration, longitudinal acceleration（in deceleration direction）and longitudinal acceleration (in acceleration direction)

scenario	date	Vehicle lateral Acceleration（Vehicle Y-axis）	AVE	σ	AVE+3σ	Vehicle longitudinal acceleration（deceleration）（Vehicle X-axis）	AVE	σ	AVE+3σ	Vehicle longitudinal acceleration（Vehicle X-axis）	AVE	σ	AVE+3σ
Open_Sky	Day1 - NL	0.8	0.9	0.12	1.3	-3.3	-4.8	0.51	-6.3	4.2	3.9	0.29	4.8
	Day2 - NL turn1	0.8				-4.3				3.5			
	Day2 - NL turn2	1.1				-5.5				5.1			
	Day2 - NL Afternoon	0.9				-4.6				4.0			
Tunnel	Day1 - NL	1.0	0.8	0.27	1.6	-5.5	-4.3	0.45	-5.6	2.9	2.9	0.17	3.3
	Day2 - NL turn1	0.9				-4.7				2.7			
	Day2 - NL turn2	0.8				-3.8				3.1			
	Day2 - NL Afternoon	0.3				-2.2				2.7			
City	Day1 - NL	1.3	1.4	0.08	1.7	-6.6	-5.2	0.09	-5.5	4.7	4.5	0.24	5.2
	Day2 - NL turn1	1.5				-5.3				4.5			
	Day2 - NL turn2	1.5				-5.3				4.1			
	Day2 - NL Afternoon	1.4				-5.1				4.7			
Mild_Urban	Day1 - NL	0.9	1.5	0.05	1.6	-5.4	-5.0	0.33	-6.0	4.9	4.6	0.32	5.5
	Day2 - NL turn1	1.5				-4.6				4.4			
	Day2 - NL turn2	1.4				-5.0				4.1			
	Day2 - NL Afternoon	2.1				-8.2				4.8			
Half_Open	Day1 - NL	1.7	0.9	0.10	1.2	-6.0	-4.3	0.10	-4.6	5.9	4.5	0.30	5.4
	Day2 - NL Afternoon1	1.0				-4.2				4.2			
	Day2 - NL Afternoon2	0.8				-4.4				4.8			
ForestA	Day3 - BE	0.7	0.7	0.05	0.8	-4.2	-4.5	1.13	-7.8	4.5	4.3	0.25	5.0
	Day4 - BE	2.0				-4.7				4.0			
	Day5 - BE	0.6				-2.8				2.2			
ForestB	Day3 - BE	0.8	0.8	0.05	0.9	-4.0	-4.0	0.05	-4.1	3.8	3.2	0.65	5.1
	Day4 - BE	0.8				-3.9				8.6			
	Day5 - BE	0.7				-4.0				2.5			
MountainA	Day3 - BE	0.7	0.6	0.05	0.8	-4.2	-3.9	0.25	-4.6	3.4	3.2	0.20	3.8
	Day4 - BE	0.6				-3.6				3.0			
	Day5 - BE	0.6				-3.8				2.3			
MountainB	Day3 - BE	0.8	0.7	0.08	0.9	-3.9	-3.9	0.05	-4.0	4.8	3.0	0.10	3.3
	Day4 - BE	0.7				-3.8				3.1			
	Day5 - BE	0.6				-2.7				2.9			
MountainC	Day3 - BE	0.7	0.7	0.05	0.8	-4.4	-4.3	0.10	-4.6	3.7	2.8	0.05	2.9
	Day4 - BE	0.7				-4.2				2.7			
	Day5 - BE	0.6				-3.4				2.8			

3.3.7.4 Test result of vehicle speed

The description of test results for vehicle speed is shown in Figure 43 which the maximum vehicle speed was 118.9 km/h in Open Sky scenario.

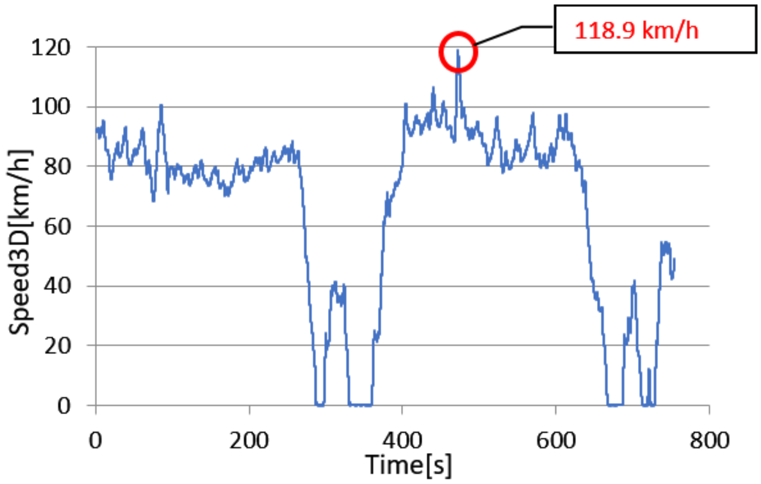


Figure 43: Results of vehicle speed

3.3.7.5 Conclusion of regular driving dynamics

The lateral acceleration and the speed values were within C2C-CC definition but the longitudinal acceleration was confirmed to exceed the requirement of C2C-CC (Table 13). CMC confirmed that PTWs are more dynamic in movement than cars and the longitudinal acceleration up to -6.0 m/s^2 (deceleration) and 5.5 m/s^2 (acceleration) may occur as a regular driving dynamics. The accuracy of positioning, speed and heading are evaluated under this condition in the following sections.

Table 13: Conclusion of regular driving dynamics

Legend

✓: Meets requirement of C2C-CC
A: No need to differentiate from car
B: Technically validated

Requirement	C2C-CC	CMC	Justification
Vehicle lateral acceleration	< 1.9 m/s^2	✓	A
Vehicle longitudinal acceleration (deceleration)	> -2.4 m/s^2	-6.0 m/s^2	B
Vehicle longitudinal acceleration	< 2.5 m/s^2	5.5 m/s^2	B
Vehicle speed	<= 130 km/h, legal Vmax of the vehicle	✓	A

3.3.8 Evaluation of position

The position confidence (95% confidence in position error) defined by C2C-CC was used to evaluate the position accuracy of the Localisation System. The obtained test data from Localisation System were compared with the ground truth system data to calculate the position confidence values of each level of Localisation System. The position confidence of u-blox M8U was also calculated. Refer to the next section for details on the calculation method.
The position confidence of each scenario obtained was evaluated in comparison with the C2C-CC requirement.

3.3.8.1 Data analysis method

Data analysis consists of the following steps after recording (Figure 44):

I. Post-process – Calculate geographical positioning information.

II. Cutout - Start and end point of the data for each scenario are matched to C2C-CC.

III. Projection - The position is evaluated on the horizontal components of the test system (Localisation System and u-blox M8U) and the ground truth system (RT3003). PROJ library[4] is used as projection tool. EPSG: 28992 (Netherlands) and EPSG: 31370 (Belgium) are selected to transform the WGS84 coordinate to 2-dimension coordinate. By selecting the EPSG code, error due to coordinate transformation can be suppressed.

IV. Interpolation- As the sampling frequency of the test system and the ground truth system are asynchronous, the information of the ground truth system is interpolated based on time synchronized with each test system.

V. Error calculation and sliding window- The position error is defined as the distance between the position reported by the test system and the position reported by the ground truth system at the same moment in time. To report the accuracy, 95% confidence of position error within the time window set to 120 seconds in accordance with C2C-CC confidence requirements was calculated. The time window is slid at 1 second interval. For each set of 120 seconds data, it is judged as "pass" if 95% confidence value is within the requirement of C2C-CC.

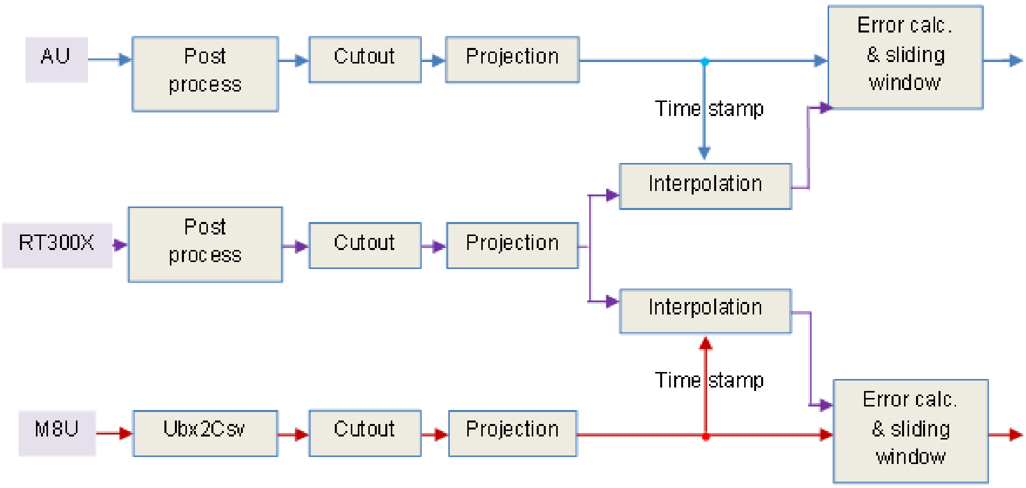


Figure 44: Analysis procedure

[4] PROJ (https://proj.org/ accessed on 06.11.2020)

3.3.8.2 Test result of position

The test results and discussions of the scenarios noted in 3.3.6 are described in the following sections. Typical test results are shown by avoiding the best or worst results among the test results of each scenario.

3.3.8.2.1 Open Sky

C2C-CC definition of the Open Sky scenario: *Sky is less than 20% obstructed, with vehicle moving with regular driving dynamics, normal road conditions.*
Figure 45 shows the measurement result of Localisation System Level 4 and Figure 46 shows the result of u-blox M8U.

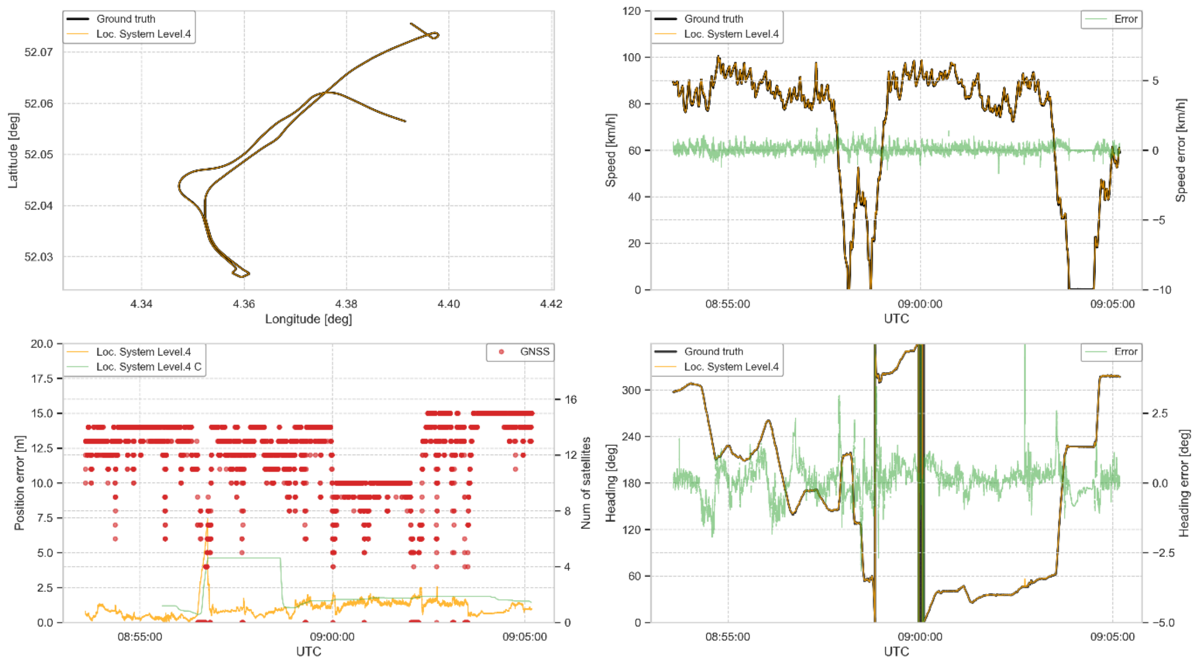


Figure 45: Measurement result of Localisation System Level 4

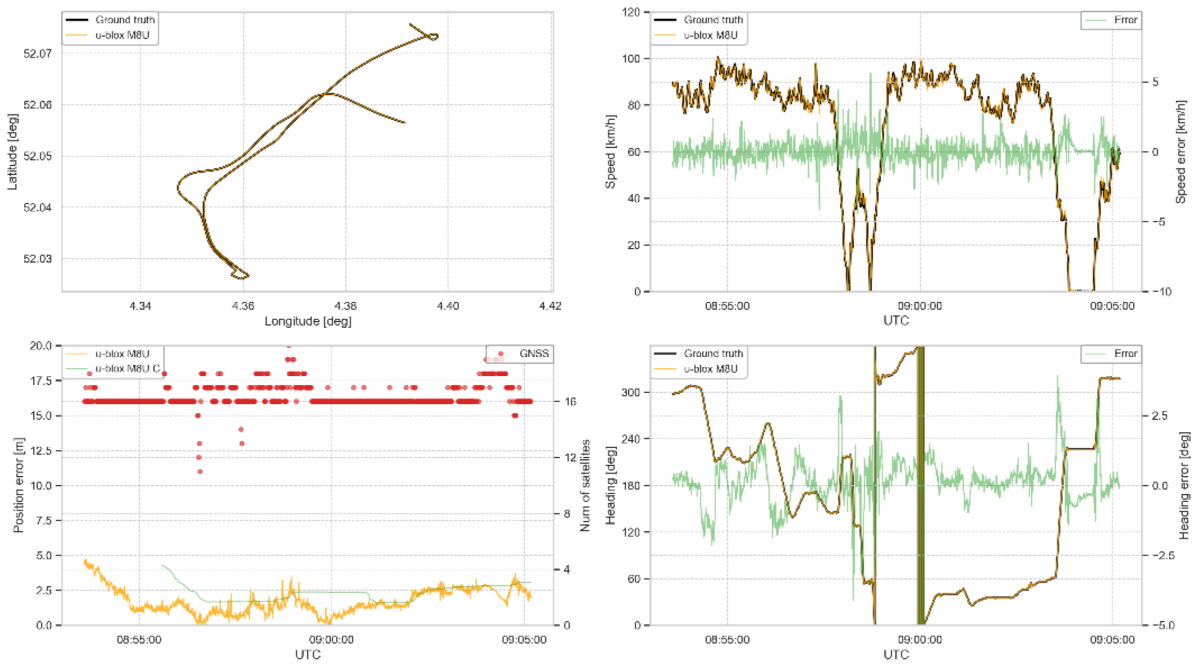


Figure 46: Measurement result of u-blox M8U

Note) The following data are shown as the measurement results of each Localisation System.

<Upper left>

Yellow line: the trajectory of Localisation System Level 4 / u-blox M8U

Black line: the trajectory of ground truth data

<Lower left>

Yellow line: the position error [m] (difference of the position measured by Localisation System/ u-blox M8U and ground truth system)

Red dots: the number of satellites used by Localisation System / u-blox M8U

Green line: the 95% confidence value calculated by position error of Localisation System Level 4/ u-blox M8U

<Upper right>

Yellow line: the vehicle speed [km/h] measured by Localisation System / u-blox M8U

Black line: the vehicle speed [km/h] measured by ground truth system

Green line: the speed error [km/h] (difference of the speed measured by Localisation System/ u-blox M8U and ground truth system)

<Lower right>

Yellow line: the vehicle heading [deg] measured by Localisation System / u-blox M8U

Black line: the vehicle heading [deg] measured by ground truth system

Green line: the heading error [deg] (difference of the heading measured by Localisation System/ u-blox M8U and ground truth system)

3.3.8.2.1.1 *Result of Open Sky*

As shown in Table 14, Localisation System Level 4 and u-blox M8U fulfilled the requirement of C2C-CC.

Table 14: Detail of data (open sky)

Run No.	Start location (lat, lon)	End location (lat, lon)	Start Time	End Time	Test System	95% Confidence[m]	C2C-CC Requirement
4	52.056487, 4.391396	52.0756, 4.392584	8:53:35	9:05:11	Loc. System Level 1	60.78	C < 5 m
					Loc. System Level 2	57.14	
					Loc. System Level 3	5.80	
					Loc. System Level 4	**2.87**	
					u-blox M8U	**4.65**	

3.3.8.2.1.2 *Discussion of the results of Open Sky*

1) The reason why Localisation System Level 1 and 2 which rely on stand-alone GNSS measurement did not satisfy the C2C-CC requirement is considered as follows:
Figure 47 shows that the number of GNSS satellites decreases when the vehicle passed under the overpass in the test route from 8:56:30 till 8:56:35.
This reduction of the number of satellites caused the deterioration of the position accuracy of Localisation System Level 1 and 2.
On the other hand, u-blox M8U maintained sufficient numbers of satellites even passing through the overpass whereas that of Localisation System decreases to zero.
One of the reasons regarding the difference between the Localisation System and the u-blox M8U is assumed to be the difference of sensitivity of the GNSS antenna. Localisation System Level 1 and 2 may satisfy the requirement if GNSS antenna with better reception sensitivity is used.

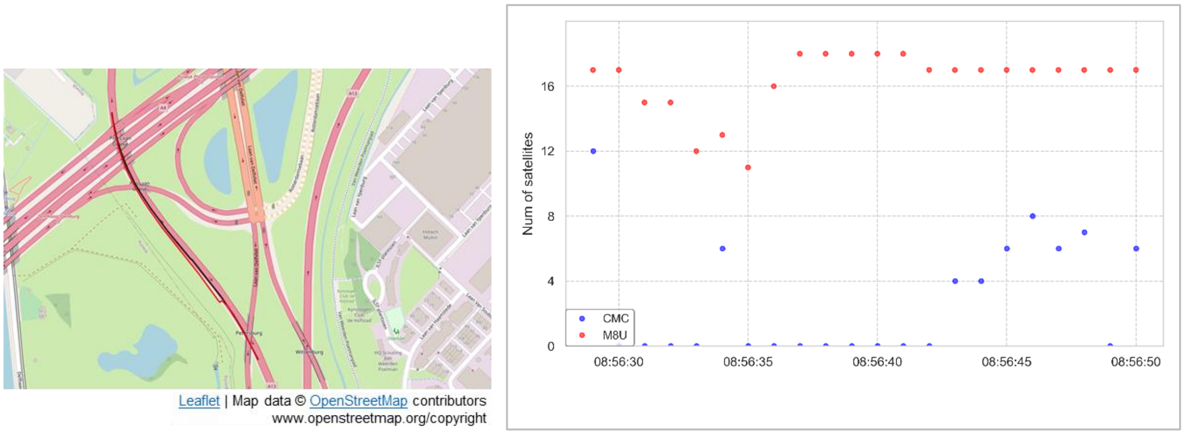


Figure 47: Plot location and number of satellites used in Open Sky

2) The reason why Localisation System Level 3 which equips position estimation technology by DR did not satisfy C2C-CC requirement is considered as follows:
It is considered that the influence of the deviation of the stand-alone GNSS positioning accuracy mentioned earlier compromised the position accuracy of Localisation System Level 3. As a reference, Figure 48 shows that the position accuracy of Localisation System Level 1 was compromised by the reduction of the number of satellites.

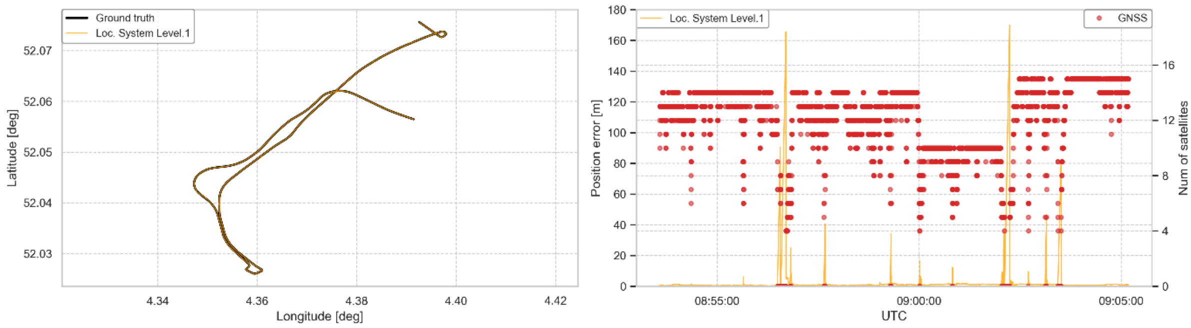


Figure 48: Measurement result of Localisation System Level 1

3.3.8.2.2 Tunnel

C2C-CC definition of the Tunnel scenario: *Sky is 100% obstructed for at least 30 s and 250 m (vmin = 30 km/h); GNSS signal reflection at entrance and end of tunnel.*

Figure 49 shows the measurement result of Localisation System Level 4 and Figure 50 shows the result of u-blox M8U.

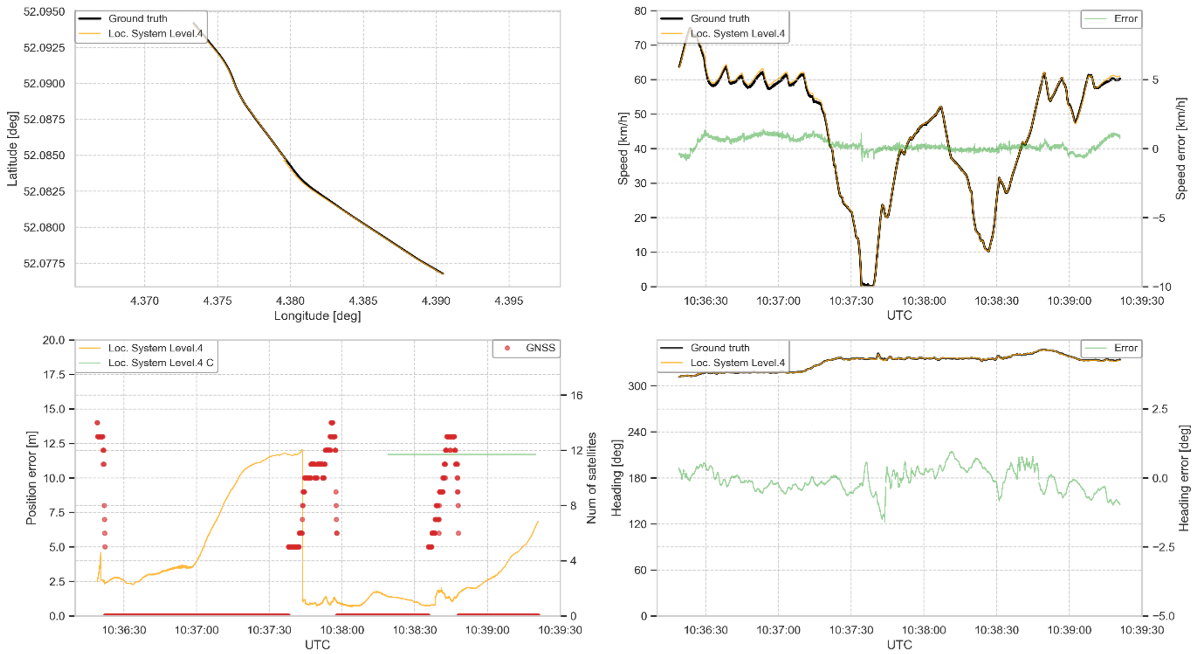


Figure 49: Measurement result of Localisation System Level 4

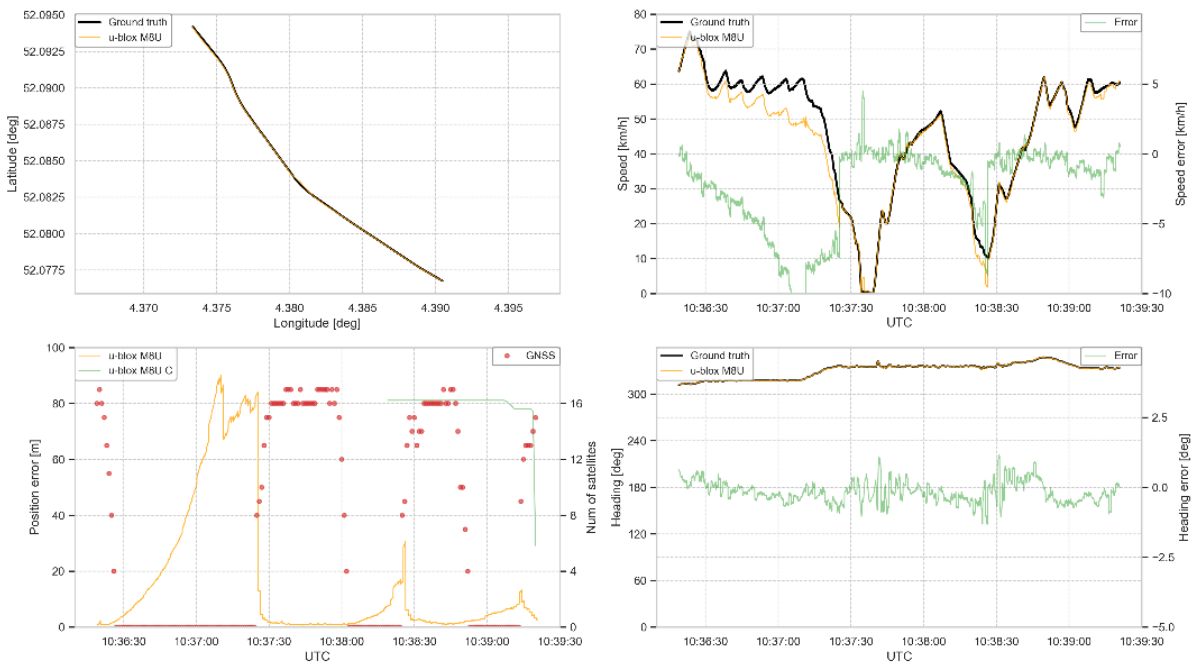


Figure 50: Measurement result of u-blox M8U

3.3.8.2.2.1 *Result of Tunnel*

As shown in Table 15, only Localisation System Level 4 fulfilled the requirement of C2C-CC.

Table 15: Detail of data (Tunnel)

Run No.	Start location (lat, lon)	End location (lat, lon)	Start Time	End Time	Test System	95% Confidence[m]	Requirement
1	52.076759, 4.390550	52.094249, 4.373307	10:36:19	10:39:21	Loc. System Level 1	1168.28	C < 15 m
					Loc. System Level 2	647.11	
					Loc. System Level 3	101.86	
					Loc. System Level 4	**14.38**	
					u-blox M8U	88.57	

3.3.8.2.2.2 *Discussion of the result of Tunnel*

1) The reason why Localisation System Level 1 and 2 which rely on stand-alone GNSS measurement did not fulfil the requirement of C2C-CC is considered as follows:
The complete lack of GNSS positioning information caused the deterioration of position accuracy.

2) The reason why Localisation System Level 3 and u-blox M8U which equips Level 3 solution did not fulfil the requirement of C2C-CC is considered as follows:
The difference between Localisation System Level 4 which satisfied the requirement and Localisation System Level 3 and u-blox M8U is whether to utilize speed pulse or not.
As shown in upper right of Figure 50, the speed error of u-blox M8U increased as the progression of time resulting in maximum of 12 km/h and this is assumed to be the cause of the result. The accumulation of the error is caused by the integral calculation of acceleration and it can be solved by utilizing speed pulses from vehicle and this means Level 4 solution or equivalent is needed to satisfy the requirement under Tunnel scenario.

3.3.8.2.3 City

C2C-CC definition of the City scenario: *In a 300 s drive, the sky was 30 - 50% obstructed (short periods of less than 30 - 50% obstructions allowed), frequent GNSS signal reflection off buildings, including short losses of GNSS signal (i.e. fewer than 4 satellites); driving conditions as Open Sky)*

Figure 51 shows the measurement result of Localisation System Level 4 and Figure 52 shows the result of u-blox M8U.

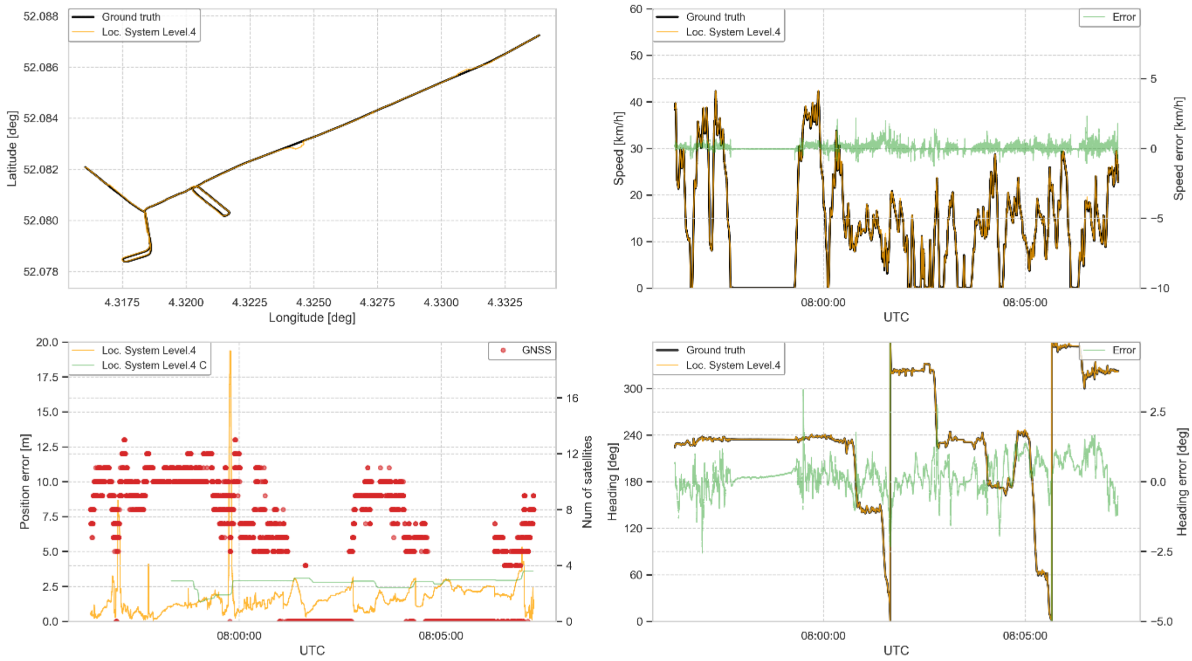


Figure 51: Measurement result of Localisation System Level 4

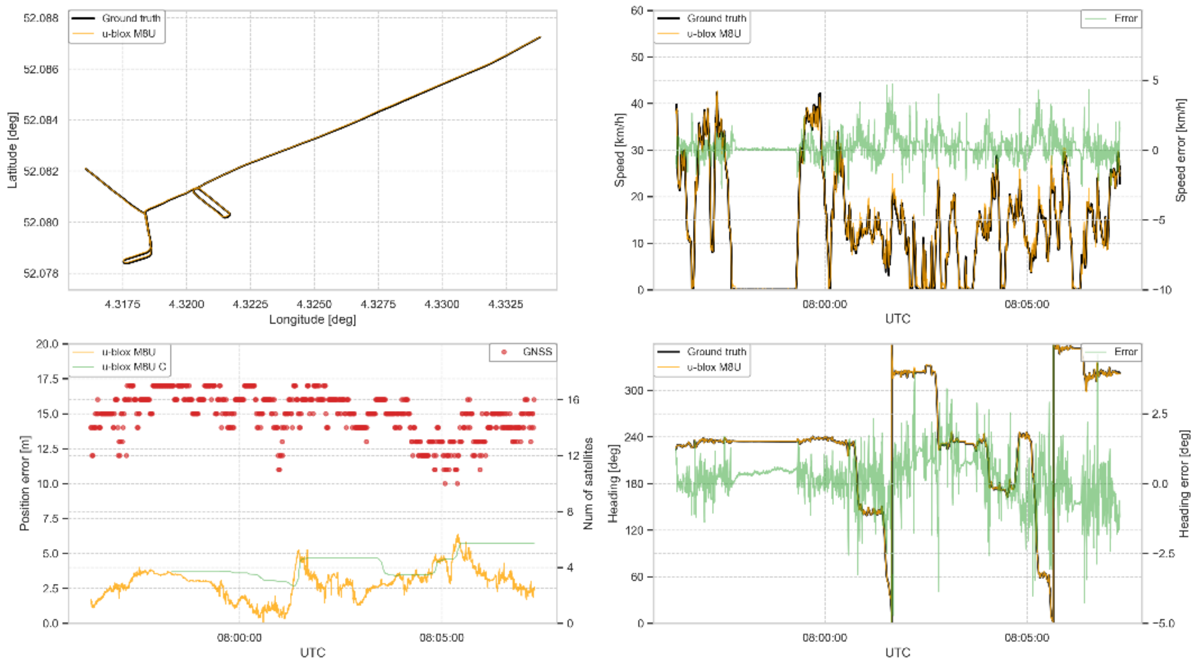


Figure 52: Measurement result of u-blox M8U

3.3.8.2.3.1 *Result of City*

As shown in Table 16, Localisation System Level 4 and u-blox M8U fulfilled the requirement of C2C-CC.

Table 16: Detail of data (City)

Run No.	Start location (lat, lon)	End location (lat, lon)	Start Time	End Time	Test System	95% Confidence[m]	Requirement
3	52.087248, 4.333839	52.08208, 4.316050	7:56:19	8:07:18	Loc. System Level 1	161.91	C < 14 m
					Loc. System Level 2	663.74	
					Loc. System Level 3	221.26	
					Loc. System Level 4	**10.63**	
					u-blox M8U	**5.81**	

3.3.8.2.3.2 *Discussion of the results of City*

The reason why u-blox M8U outperformed Level 4 which uses more types of sensors is considered as follows:
It is assumed to be that u-blox M8U was able to maintain satellite reception numbers supported by higher sensitivity of GNSS antenna which was the case in the Open Sky scenario.

3.3.8.2.4 Mild Urban

C2C-CC definition of the Mild Urban scenario: *Sky is 20 - 40% obstructed, t > 60 s, s > 400 m. Driving conditions as Open Sky, with stops, trees and/or buildings, as well as alleys*
Figure 53 shows the measurement result of Localisation System Level 4 and Figure 54 shows the result of u-blox M8U.

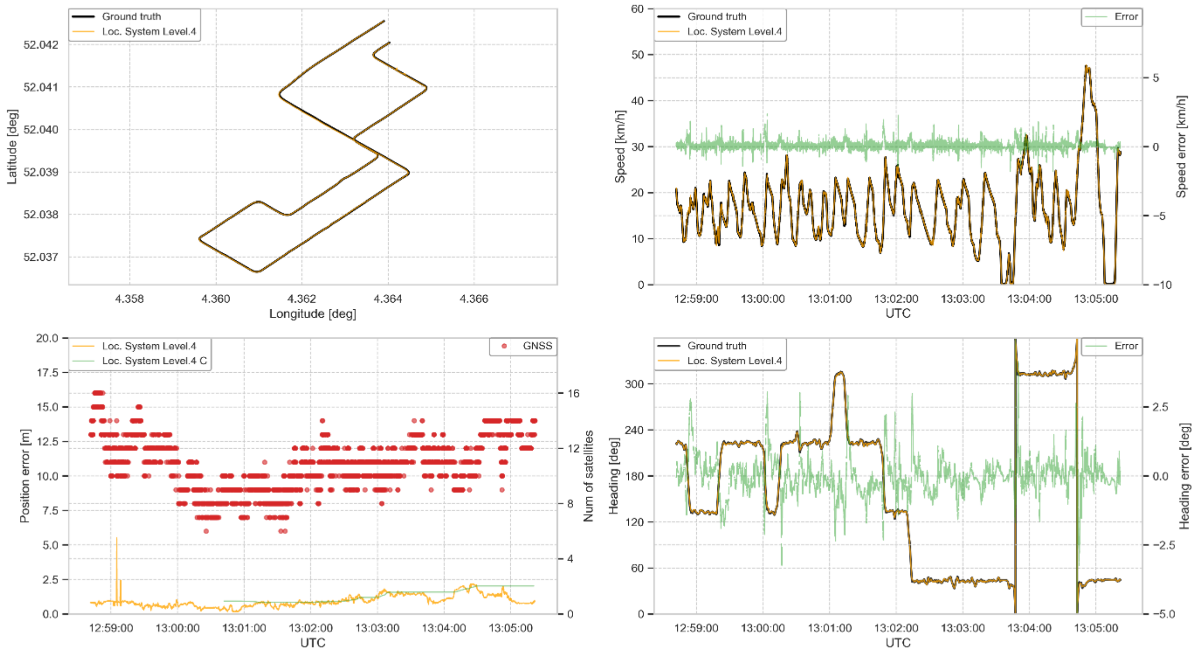


Figure 53: Measurement result of Localisation System Level 4

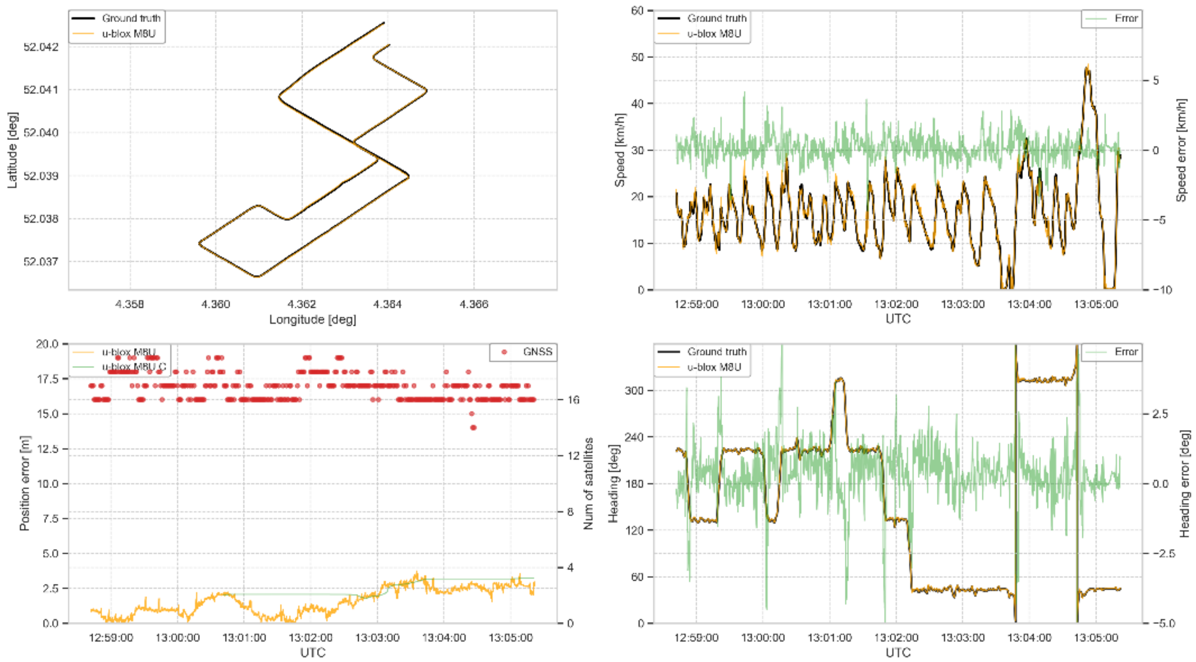


Figure 54: Measurement result of u-blox M8U

3.3.8.2.4.1 *Result of Mild Urban*

As shown in Table 17, Localisation System Level 1-4 and u-blox M8U fulfilled the requirement of C2C-CC.

Table 17: Detail of data (Mild Urban)

Run No.	Start location (lat, lon)	End location (lat, lon)	Start Time	End Time	Test System	95% Confidence[m]	Requirement
5	52.042024, 4.364013	52.042476, 4.363793	12:58:42	13:05:21	Loc. System Level 1	**2.34**	C < 10 m
					Loc. System Level 2	**2.14**	
					Loc. System Level 3	**2.10**	
					Loc. System Level 4	**2.11**	
					u-blox M8U	**3.59**	

3.3.8.2.4.2 *Discussion of the results of Mild Urban*

The reason why Localisation System Levels 1 and 2 which rely on stand-alone GNSS positioning without DR were able to fulfill the requirement is considered as follows:
It is assumed that the sufficient number of satellite reception was maintained throughout the route. The number of satellites measured by Localisation System in the Mild Urban scenario is shown in Figure 55.

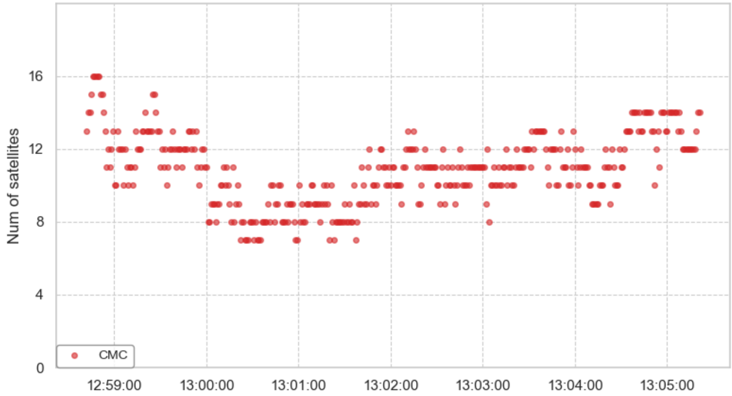


Figure 55: Number of satellites Localisation System used while Mild Urban

As a result, stand-alone GNSS positioning enables accuracy of approximately 2 meters when sufficient number of received satellite is observed.

3.3.8.2.5 Mountain

C2C-CC definition of the Mountain scenario: *Sky is 40 - 60% obstructed by high mountain(s); driving conditions as Open Sky.*

Figure 56 shows the measurement result of Localisation System Level 4 and Figure 57 shows the result of u-blox M8U.

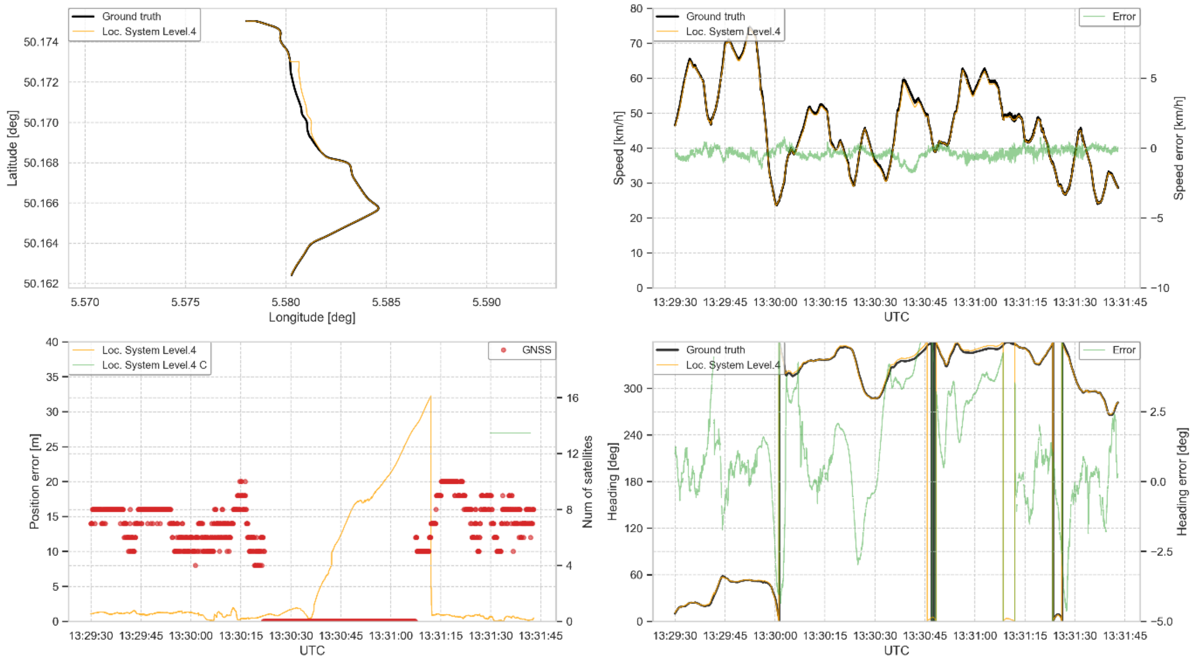


Figure 56: Measurement result of Localisation System Level 4

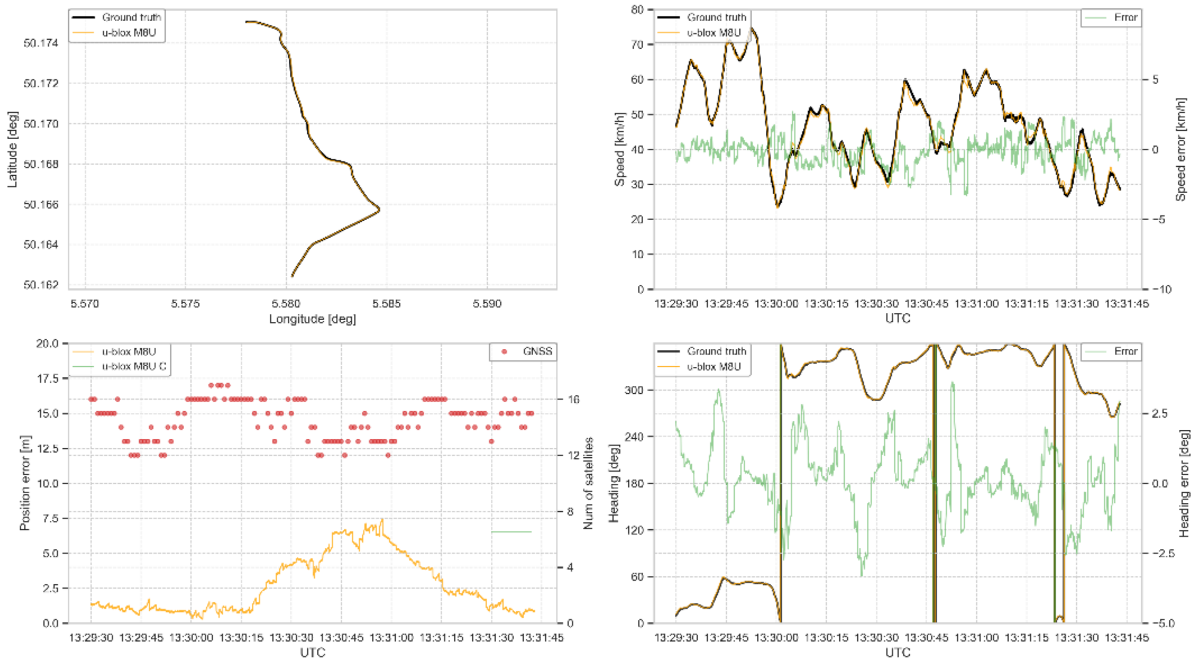


Figure 57: Measurement result of u-blox M8U

3.3.8.2.5.1 *Result of Mountain*

As shown in Table 18, only u-blox M8U fulfilled the requirement of C2C-CC.

Table 18: Detail of data (Mountain)

Run No.	Start location (lat, lon)	End location (lat, lon)	Start Time	End Time	Test System	95% Confidence[m]	Requirement
9	50.16240, 5.5802	50.175040, 5.578031	13:29:30	13:31:43	Loc. System Level 1	408.43	C < 10 m
					Loc. System Level 2	966.17	
					Loc. System Level 3	407.21	
					Loc. System Level 4	21.64	
					u-blox M8U	**6.97**	

3.3.8.2.5.2 *Discussion of the results of Mountain*

The reason why Localisation System, especially Level 4, did not fulfill the requirement is considered as follows:
The time when no satellites were observed was about 1 minute during which the position estimation by DR was carried out, but the estimation accuracy was assumed not to be sufficient (Figure 56). Although the elapsed time of DR positioning was shorter than Tunnel scenario of 3 minutes, the heading error increased because the driving route was not a simple straight path such as in the measurement of the tunnel.
To improve heading accuracy, adopting more precise IMU or improving DR positioning algorithms are needed.

3.3.8.2.6 Forest

C2C-CC definition of the Forect scenario: *Sky is 30 - 50% obstructed by objects including trees higher than the antenna, for more than 30 s*

Figure 58 shows the measurement result of Localisation System Level 4 and Figure 59 shows the result of u-blox M8U.

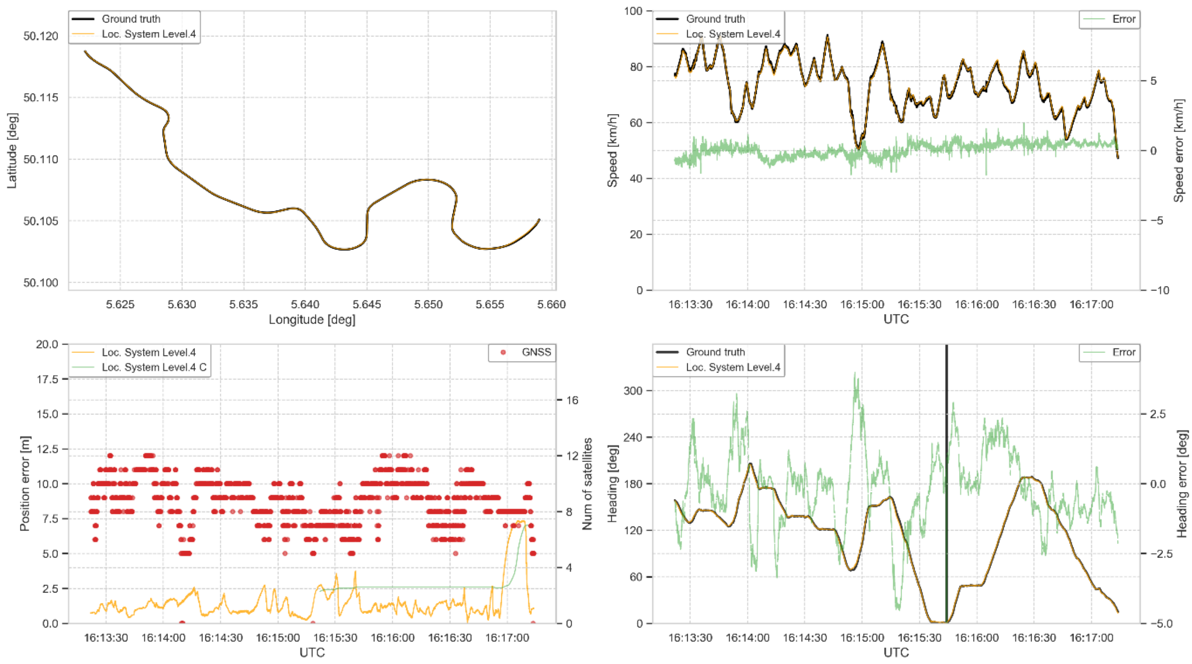


Figure 58: Measurement result of Localisation System Level 4

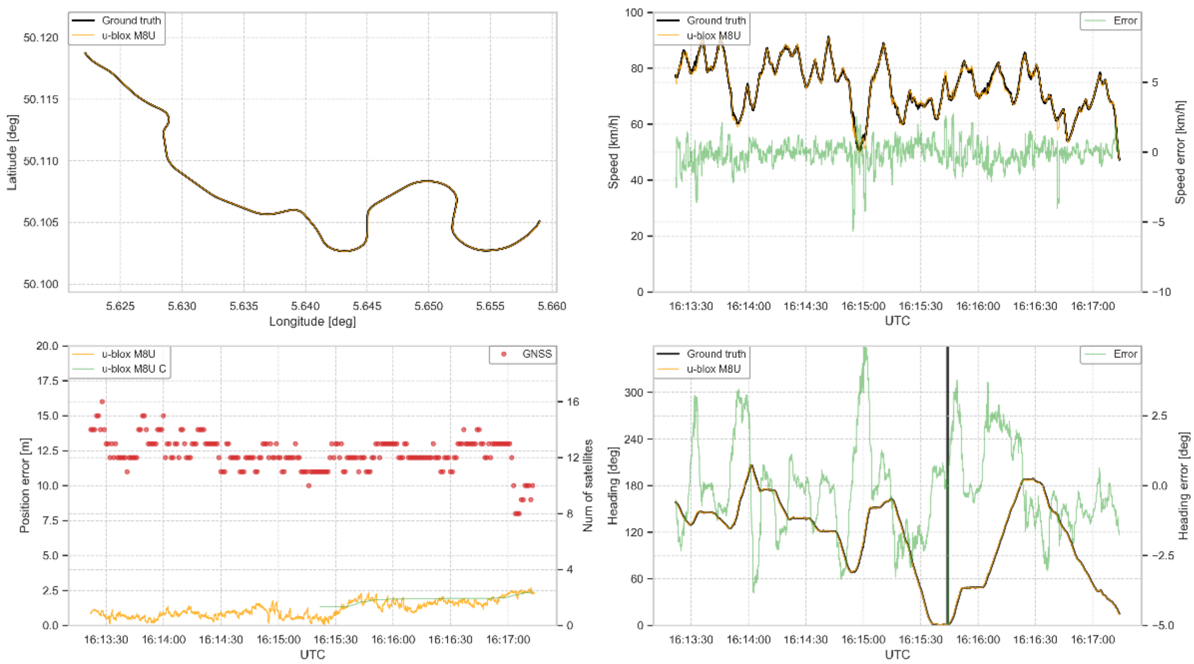


Figure 59: Measurement result of u-blox M8U

3.3.8.2.6.1 *Result of Forest*

As shown in Table 19, Localisation System Levels 3 and 4 and u-blox M8U fulfilled the requirement of C2C-CC.

Table 19: Detail of data (Forest)

Run No.	Start location (lat, lon)	End location (lat, lon)	Start Time	End Time	Test System	95% Confidence[m]	Requirement
8	50.118785, 5.622117	50.105099, 50.65898	16:13:22	16:17:14	Loc. System Level 1	11.74	C < 10 m
					Loc. System Level 2	11.46	
					Loc. System Level 3	**5.37**	
					Loc. System Level 4	**5.16**	
					u-blox M8U	**2.61**	

3.3.8.2.6.2 *Discussion of the results of Forest*

The reason why Localisation System Levels 1 and 2 did not fulfil requirement of C2C-CC is considered as follows:

There was a situation where the satellite environment was poor and the number of observed satellites dropped to less than ten (Figure 60). This situation caused the deterioration of positioning accuracy.

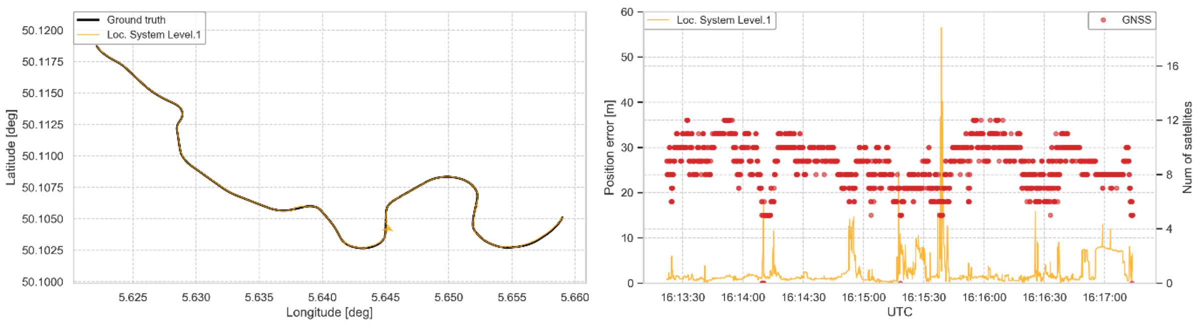


Figure 60 Measurement result of Localisation System Level 1

3.3.8.2.7 Half Open Sky

C2C-CC definition of the Half Open Sky scenario: *Sky is 30 - 50% obstructed (obstruction concentrated on one side of the car) for more than 30 s; driving conditions as Open Sky*

To demonstrate Half Open Sky scenario, half of the antenna of the test system was covered with aluminum foil (Figure 61). The driving route is identical to the Open Sky scenario.

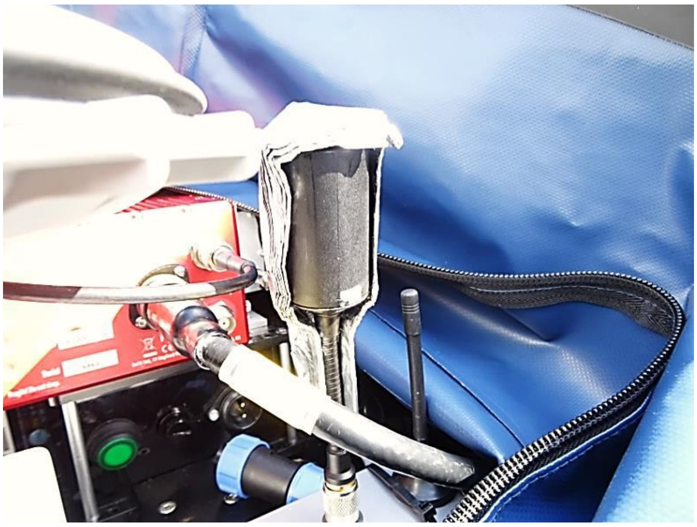


Figure 61: Antenna in the case of Half Open Sky scenario

Figure 62 shows the measurement result of Localisation System Level 4 and Figure 63 shows the result of u-blox M8U.

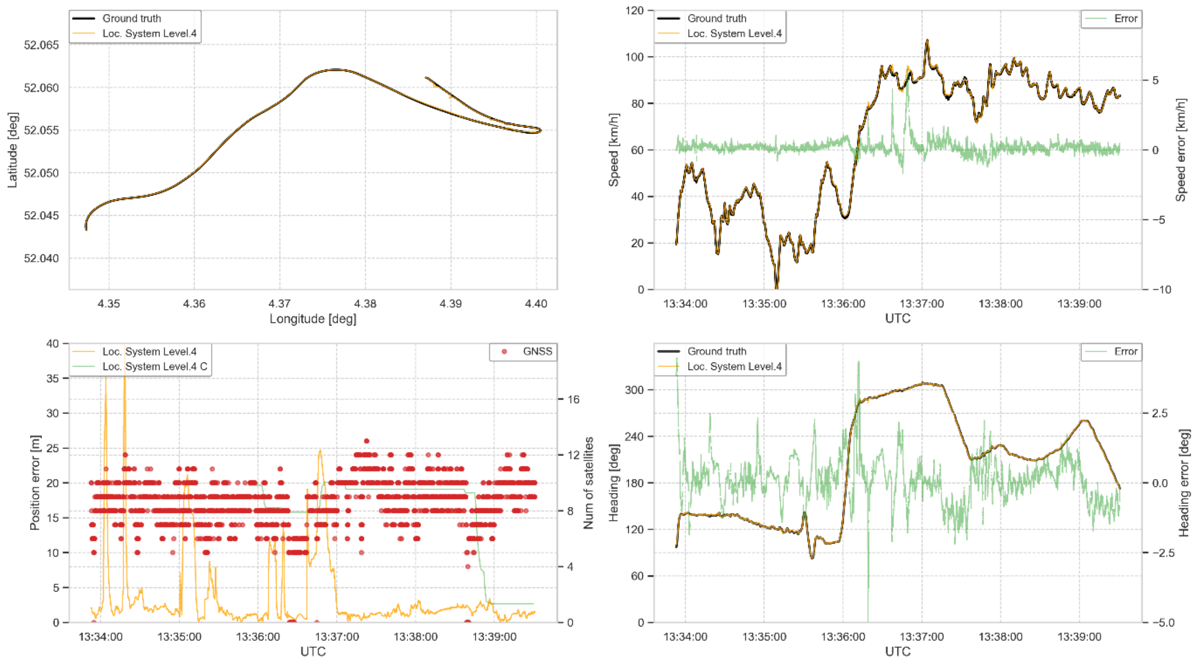


Figure 62: Measurement result of Localisation System Level 4

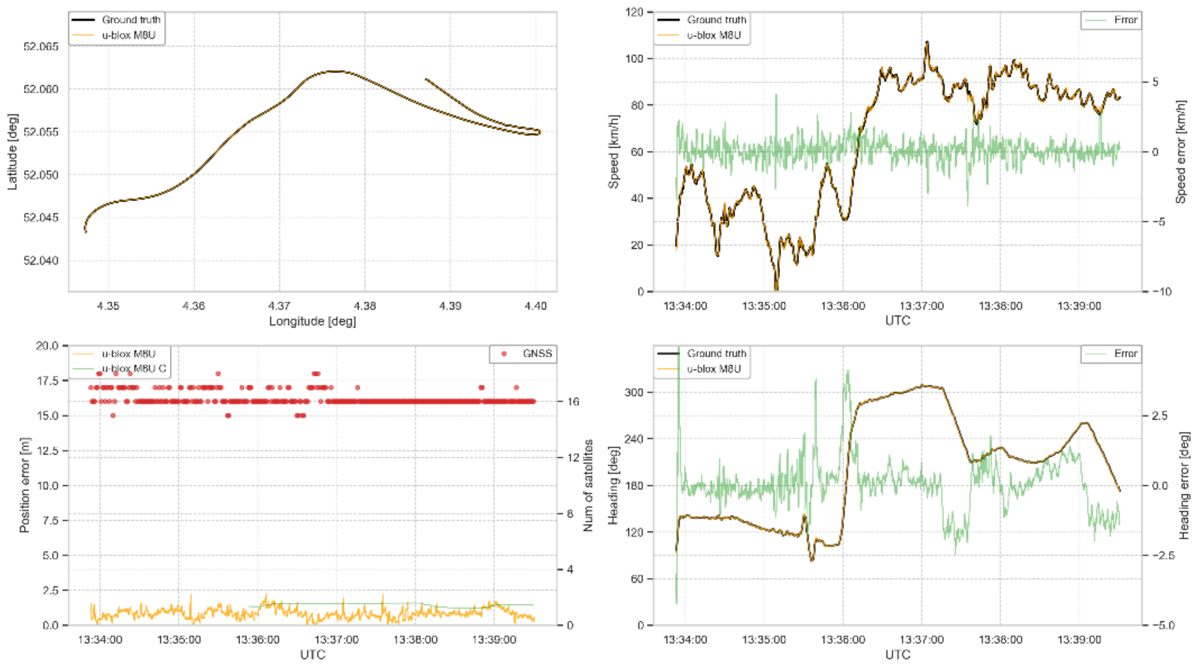


Figure 63: Measurement result of u-blox M8U

3.3.8.2.7.1 *Result of Half Open Sky*

As shown in Table 20, only u-blox M8U fulfilled the requirement of C2C-CC.

Table 20: Detail of data (Half Open Sky)

Run No.	Start location (lat, lon)	End location (lat, lon)	Start Time	End Time	Test System	95% Confidence[m]	Requirement
6	52.055349, 4.399263	52.054966, 4.395630	13:35:53	13:45:59	Loc. System Level 1	24.33	C < 7 m
					Loc. System Level 2	21.77	
					Loc. System Level 3	24.01	
					Loc. System Level 4	15.41	
					u-blox M8U	**1.77**	

3.3.8.2.7.2 *Discussion of the results of Half Open Sky*

For the Localisation System, simulating Half Open Sky scenario (to limit the reception of satellites by using aluminium-foil) was considered successful. The number of satellites have been reduced to approximately eight on average.

The reason why Localisation System, even Level 4, did not satisfy C2C-CC requirement is considered as follows:

The position estimation accuracy was not sufficient due to the deterioration of stand-alone GNSS positioning accuracy (Figure 64) despite fulfilling minimum required number of satellites.

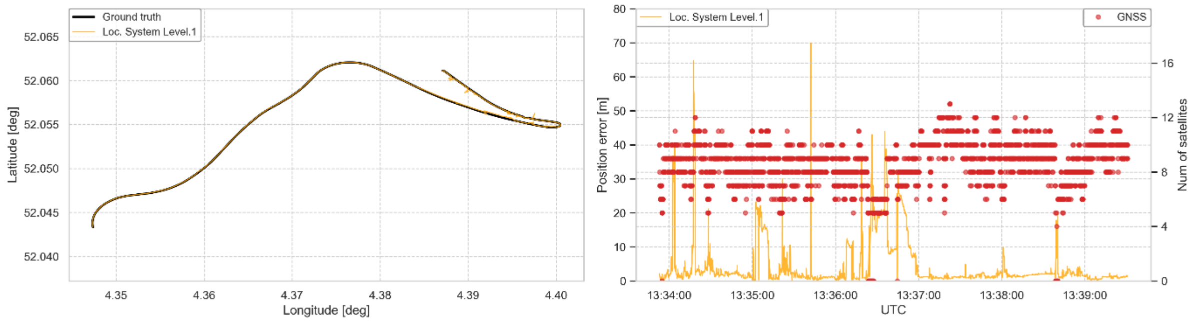


Figure 64: Measurement result of Localisation System Level 1

For u-blox M8U, it was impossible to reduce the number of satellites covering the antenna with aluminium foil. The reason is assumed to have been related to different types of antenna. Antenna is equipped with radiating element inside which enables reception of satellite signals. Patch type antenna was used with u-blox M8U, where the radiating element is forming a planar arrangement inside the plate type antenna. Parts of the radiating element were therefore completely exposed even when half of the antenna body is covered and therefore the number of satellites was assumed to not have been reduced to half.

3.3.8.3 Conclusion of position

Table 21 shows the C2C-CC requirement and the results of the position confidence of Localisation System and u-blox M8U.

Table 21: Test scenarios and requirements

Legend
✓: Meets requirement of C2C-CC
A: No need to differentiate from car
B: Technically validated

Scenario	C2C-CC Requirement	u-blox M8U		Localisation System	
		Result	Justification	Result	Justification
Open Sky	C < 5 m	✓	A	✓	A, Level 4
Tunnel	C < 15 m	88.57 m	B	✓	A, Level 4
City	C < 14 m	✓	A	✓	A, Level 4
Mild Urban	C < 10 m	✓	A	✓	A, Level 1 - 4
Mountain	C < 10 m	✓	A	21.64 m	B, Level 4
Forest	C < 10 m	✓	A	✓	A, Level 3 - 4
Half Open Sky	C < 7 m	✓	A	15.41 m	B, Level 4

C = Position confidence

1) Localisation System Level 4
It failed to fulfill the requirements of C2C-CC for Mountain and Half Open Sky scenarios. To fulfil the requirements of C2C-CC, the following measures shall be taken to improve the position accuracy to fulfill the requirements.

- Improvement of DR positioning (Particularly the heading estimation)
  Lack of the vehicle heading estimation accuracy in Mountain scenario was indicated when the location estimation by DR for long period of time was necessary. One solution for improving the heading estimation is to use an IMU with better precision and higher calculation rate. With the heading estimation algorithm used in this test, the estimation accuracy of vehicle attitude angle (Roll, Pitch, Yaw) is not mature enough hence affecting the heading accuracy. Further improvements on this algorithm are necessary.
- Choice of GNSS antenna
  Compromised location estimation accuracy of Localisation System in Half Open Sky scenario was due to low level of precision of stand-alone GNSS positioning (Level 1). Improvements of precision of stand-alone GNSS positioning is necessary in order to improve location estimation accuracy and for this reason, choosing antenna with good receiving sensitivity is effective. With this measure, there is a possibility of fulfilling the requirements of C2C-CC for Open Sky by stand-alone GNSS positioning.

2) u-blox M8U
This device was able to fulfil the requirements of C2C-CC except for the Tunnel scenario. However, u-blox provides the possibility to improve accuracy by connecting GNSS with speed information (i.e. by wheel tick sensor) which then is thought to fulfill the requirements of C2C-CC.

In the Half Open Sky scenario, when adopting the patch type GNSS antenna, even if the half of the antenna body is covered with aluminum foil, there is no reduction in the number of satellites. Therefore, the evaluation method of the Half Open Sky when using this type of antenna remains the challenge.

3.3.9 Evaluation of speed and heading

The evaluation of the speed and heading accuracy of Localisation System and u-blox M8U is explained in the following sections.
The speed/heading confidence (95% confidence value) defined by C2C-CC was used to evaluate the speed/heading accuracy of the Localisation System. The obtained speed/heading data from Localisation System were compared with the ground truth system data to calculate the speed/heading confidence values of each level of Localisation System. The speed/heading confidence of u-blox M8U was also calculated. Details on the calculation method are described in the next section.
The speed/heading confidence of each scenario obtained was evaluated in comparison with the requirements of C2C-CC.

3.3.9.1 Data analysis method

Data analysis consists of the following steps after recording:

I. Calculate speed error and heading error between the test system (Localisation System and u-blox M8U) and the ground truth system (RT3003).
II. Filtering speed error and heading error by vehicle speed "greater than 12.5 m/s" or "between 1.4 m/s and 12.5 m/s" for the Open Sky scenario and “greater than or equal to 1.4 m/s” for other scenarios.
III. Calculate 95% confidence values of speed error and heading error within the time window set to 120 seconds.
IV. For each set of 120 seconds data, it is judged as “pass” if 95% confidence values are less than the requirements of C2C-CC.

3.3.9.2 Test result

The Table 22 to Table 28 show the results of speed and heading confidence of Localisation System and u-blox M8U for each scenario. The results which fulfill requirements of C2C-CC are shown in bold. (Confidence values need to be lower than requirement values.)

Table 22: Speed and heading (Open Sky)

Run No.	Test System	Speed Confidence [m/s]		Speed Requirement [m/s]		Heading confidence [deg]		Heading Requirement [deg]	
		Greater than 12.5 m/s	Between 1.4 m/s and 12.5 m/s	Greater than 12.5 m/s	Between 1.4 m/s and 12.5 m/s	Greater than 12.5 m/s	Between 1.4 m/s and 12.5 m/s	Greater than 12.5 m/s	Between 1.4 m/s and 12.5 m/s
4	Loc. System Level 1	1.43	**0.59**	0.3 m/s	0.6 m/s	**1.08**	**1.36**	2 deg	3 deg
	Loc. System Level 2	1.40	1.37			2.36	4.43		
	Loc. System Level 3	0.57	**0.42**			**0.34**	**1.07**		
	Loc. System Level 4	**0.28**	**0.29**			**0.33**	**1.04**		
	u-blox M8U	0.65	0.89			**0.33**	**0.93**		

Table 23: Speed and heading (Tunnel)

Run No.	Test System	Speed Confidence [m/s]	Speed Requirement [m/s]	Heading Confidence [deg]	Heading Requirement [deg]
		v >= 1.4 m/s	v >= 1.4 m/s	v >= 1.4 m/s	v >= 1.4 m/s
1	Loc. System Level 1	11.91	C <= 0.6 m/s (for parts of the scenario with v >= 1.4 m/s, otherwise any value allowed) (C = SpeedConfidence)	**7.67**	12 degrees (for parts of the scenario with v >= 1.4 m/s, otherwise any value allowed)
	Loc. System Level 2	20.87		**7.19**	
	Loc. System Level 3	6.20		**0.54**	
	Loc. System Level 4	**0.48**		**0.63**	
	u-blox M8U	3.71		**0.54**	

Table 24: Speed and heading (City)

Run No.	Test System	Speed Confidence [m/s]	Speed Requirement [m/s]	Heading Confidence [deg]	Heading Requirement [deg]
		v >= 1.4 m/s	v >= 1.4 m/s	v >= 1.4 m/s	v >= 1.4 m/s
3	Loc. System Level 1	5.20	C <= 0.6 m/s (for parts of the scenario with v >= 1.4 m/s, otherwise any value allowed) (C = SpeedConfidence)	83.26	12 degrees (for parts of the scenario with v >= 1.4 m/s, otherwise any value allowed)
	Loc. System Level 2	95.54		66.32	
	Loc. System Level 3	7.43		**5.01**	
	Loc. System Level 4	**0.28**		**3.40**	
	u-blox M8U	0.92		**1.69**	

Table 25: Speed and heading (Mild Urban)

Run No.	Test System	Speed Confidence [m/s]	Speed Requirement [m/s]	Heading Confidence [deg]	Heading Requirement [deg]
		v >= 1.4 m/s	v >= 1.4 m/s	v >= 1.4 m/s	v >= 1.4 m/s
5	Loc. System Level 1	**0.50**	C <= 0.6 m/s (for parts of the scenario with v >= 1.4 m/s, otherwise any value allowed) (C = SpeedConfidence)	**2.16**	6 degrees (for parts of the scenario with v >= 1.4 m/s, otherwise any value allowed)
	Loc. System Level 2	1.37		**5.11**	
	Loc. System Level 3	**0.31**		**1.01**	
	Loc. System Level 4	**0.23**		**0.94**	
	u-blox M8U	0.71		**1.27**	

Table 26: Speed and heading (Mountain)

Run No.	Test System	Speed Confidence [m/s]	Speed Requirement [m/s]	Heading Confidence [deg]	Heading Requirement [deg]
		v >= 1.4 m/s	v >= 1.4 m/s	v >= 1.4 m/s	v >= 1.4 m/s
9	Loc. System Level 1	4.56	C <= 0.6 m/s (for parts of the scenario with v >= 1.4 m/s, otherwise any value allowed) (C = SpeedConfidence)	7.31	6 degrees (for parts of the scenario with v >= 1.4 m/s, otherwise any value allowed)
	Loc. System Level 2	30.15		43.08	
	Loc. System Level 3	16.68		**2.54**	
	Loc. System Level 4	**0.37**		**1.66**	
	u-blox M8U	0.81		**0.87**	

Table 27: Speed and heading (Forest)

Run No.	Test System	Speed Confidence [m/s]	Speed Requirement [m/s]	Heading Confidence [deg]	Heading Requirement [deg]
		v >= 1.4 m/s	v >= 1.4 m/s	v >= 1.4 m/s	v >= 1.4 m/s
8	Loc. System Level 1	0.80	C <= 0.6 m/s (for parts of the scenario with v >= 1.4 m/s, otherwise any value allowed) (C = SpeedConfidence)	**0.93**	6 degrees (for parts of the scenario with v >= 1.4 m/s, otherwise any value allowed)
	Loc. System Level 2	5.91		**1.86**	
	Loc. System Level 3	0.75		**0.70**	
	Loc. System Level 4	**0.42**		**0.73**	
	u-blox M8U	0.77		**0.45**	

Table 28: Speed and heading (Half Open Sky)

Run No.	Test System	Speed Confidence [m/s]	Speed Requirement [m/s]	Heading Confidence [deg]	Heading Requirement [deg]
		v >= 1.4 m/s	v >= 1.4 m/s	v >= 1.4 m/s	v >= 1.4 m/s
6	Loc. System Level 1	1.63	C <= 0.6 m/s (for parts of the scenario with v >= 1.4 m/s, otherwise any value allowed) (C = SpeedConfidence)	**1.25**	6 degrees (for parts of the scenario with v >= 1.4 m/s, otherwise any value allowed)
	Loc. System Level 2	2.38		**2.12**	
	Loc. System Level 3	1.50		**1.09**	
	Loc. System Level 4	**0.55**		**0.68**	
	u-blox M8U	0.66		**0.36**	

3.3.9.3 Conclusion of speed and heading

Table 29 and Table 30 show the C2C-CC requirements and the results of the speed and heading confidence of Localisation System and u-blox.

Table 29: Heading requirement

Legend

✓: Meets requirement of C2C-CC
A: No need to differentiate from car
B: Technically validated

Scenario	C2C-CC Requirement		u-blox M8U		Localisation System	
			Result	Justification	Result	Justification
Open Sky	Between 1.4 m/s and 12.5 m/s	3 deg	✓	A	✓	A, Level 1, 3, 4
	Greater than 12.5 m/s	2 deg	✓	A	✓	A, Level 1 - 4
Tunnel	v >= 1.4 m/s	12 deg	✓	A	✓	A, Level 1 - 4
City	v >= 1.4 m/s	12 deg	✓	A	✓	A, Level 3 - 4
Mild Urban	v >= 1.4 m/s	6 deg	✓	A	✓	A, Level 1 - 4
Mountain	v >= 1.4 m/s	6 deg	✓	A	✓	A, Level 3 - 4
Forest	v >= 1.4 m/s	6 deg	✓	A	✓	A, Level 1 - 4
Half Open Sky	v >= 1.4 m/s	6 deg	✓	A	✓	A, Level 1 - 4

Table 30: Speed requirement

Legend
✓: Meets requirement of C2C-CC
A: No need to differentiate from car
B: Technically validated

Scenario	C2C-CC Requirement		u-blox M8U		Localisation System	
			Result	Justification	Result	Justification
Open Sky	Between 1.4 m/s and 12.5 m/s	0.6 m/s	0.75 m/s	B	✓	A, Level 1, 3, 4
	Greater than 12.5 m/s	0.3 m/s	0.63 m/s	B	✓	A, Level 4
Tunnel	v >= 1.4 m/s	0.6 m/s	5.44 m/s	B	✓	A, Level 4
City	v >= 1.4 m/s	0.6 m/s	0.92 m/s	B	✓	A, Level 4
Mild Urban	v >= 1.4 m/s	0.6 m/s	0.71 m/s	B	✓	A, Level 1, 3, 4
Mountain	v >= 1.4 m/s	0.6 m/s	0.81 m/s	B	✓	A, Level 4
Forest	v >= 1.4 m/s	0.6 m/s	0.77 m/s	B	✓	A, Level 4
Half Open Sky	v >= 1.4 m/s	0.6 m/s	0.66 m/s	B	✓	A, Level 4

1) Localisation System Level 4
It is confirmed to fulfil heading and speed requirements for all scenarios.

2) u-blox M8U
It is confirmed to fulfil heading requirements for all scenarios but failed to fulfil speed requirement for all scenarios. It is necessary to improve DR technology utilizing vehicle speed input to fulfil speed requirement.

Appendix A Motorcycle Approach Indication (MAI)

A.1 General description

The MAI is defined as a combination of applications that informs a vehicle driver that an approaching PTW is nearby, even if the driver cannot see the PTW.
If, based on movement data, a possible crossing with the PTW is detected, or the relative distance between the two vehicles decreases below a given margin, information is issued to the vehicle driver.

A.2 Use case description

This C-ITS service informs a V2V message related to the existence of oncoming PTWs to a car side for awareness of invisible or indistinct PTWs. To determine the need for notification of the V2V messages, the risk of collision is calculated briefly by oncoming PTWs data received via CAM with the ego vehicle data. When it is determined that a collision has the possibility, the time to collision is calculated constantly in the ego vehicle side. A V2V message is displayed when both vehicles approach and the calculated time before a collision is below a certain threshold. The following four use cases are assumed in this C-ITS service.

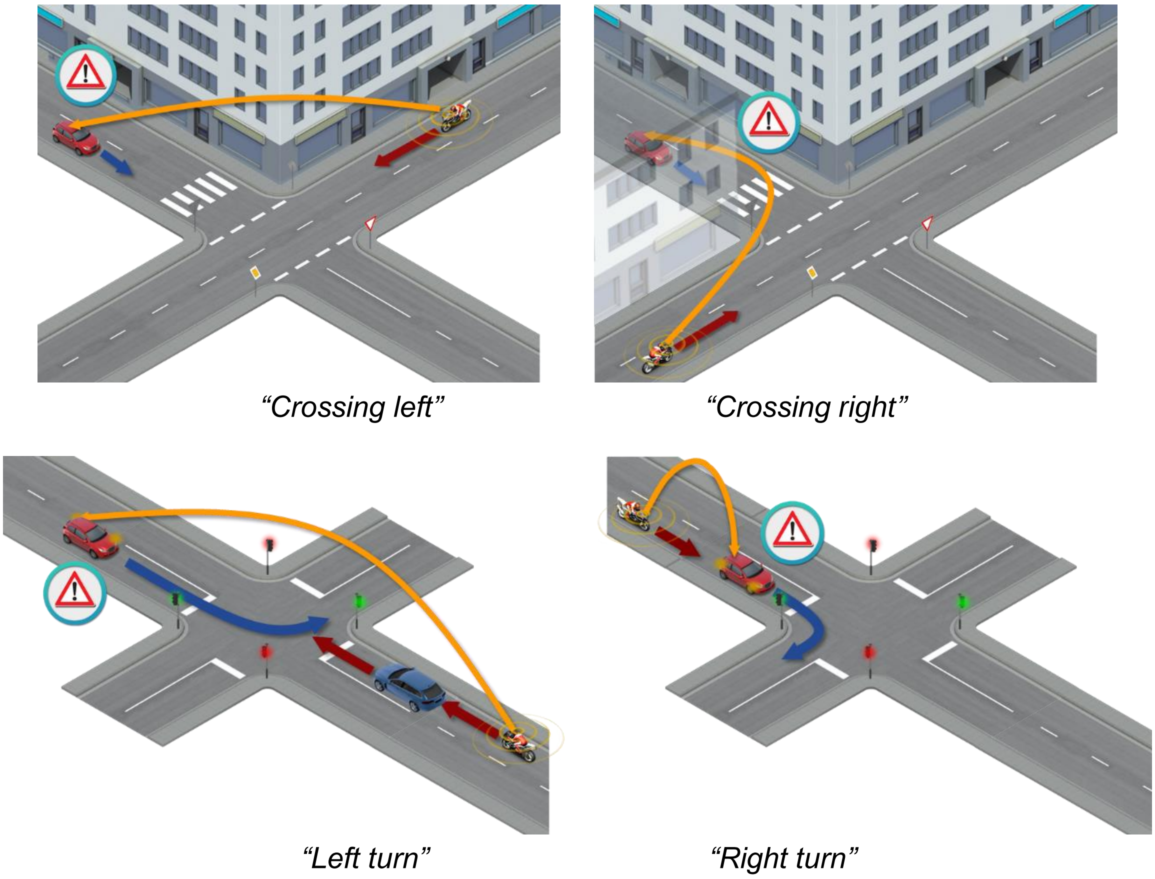
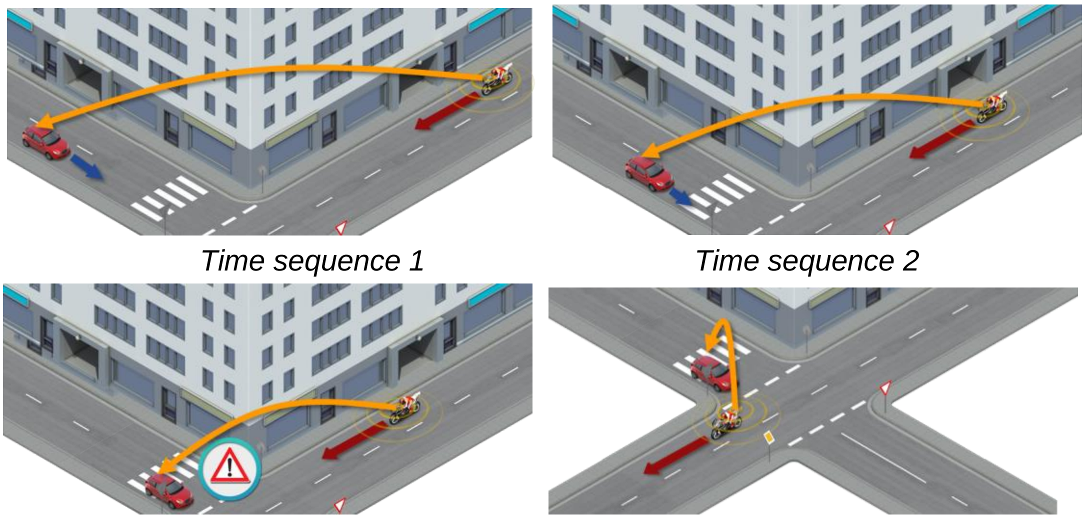


Figure A-1: Assumed use cases of MAI

A.2.1 Scenario description/perspective P3

Figure A-2 shows the use case scenario of “Crossing left” for Perspective P3. The time sequence of this scenario is as follows.



Time sequence 1 *Time sequence 2*

Time sequence 3 *Time sequence 4*

Figure A-2: use case scenario of “Crossing left”

Time sequence 1

A car and a PTW are oncoming an intersection, and the car is traveling on the side of a non-priority road. Both oncoming vehicles cannot recognize each other because of the obstacles in sight, but the car can receive the PTW's CAM over the air.

Time sequence 2

As the car approaches the intersection, MAI application running in the car combines PTW’s CAM with ego vehicle data and calculates relative distance, speed, and direction between PTW to classify the collision type as one of the use cases.

Time sequence 3

After classifying the collision type, the critical time to the collision such as TTC is calculated from the rate of change of the relative distance without predicting a collision point. When this time becomes lower than the threshold of time to inform, the MAI application indicates information that PTW is oncoming from a certain direction to the car driver.

Time sequence 4

After the PTW has passed in front of the vehicle, the critical time is calculated with the inverse sign. Therefore, the status becomes safer and the MAI application then clears the above information on the car’s HMI.

A.3 Technical description

A.3.1 Perspective P3 (receive CAM)

A.3.1.1 State flow

The following is the state machine diagram of the MAI application for Perspective P3.

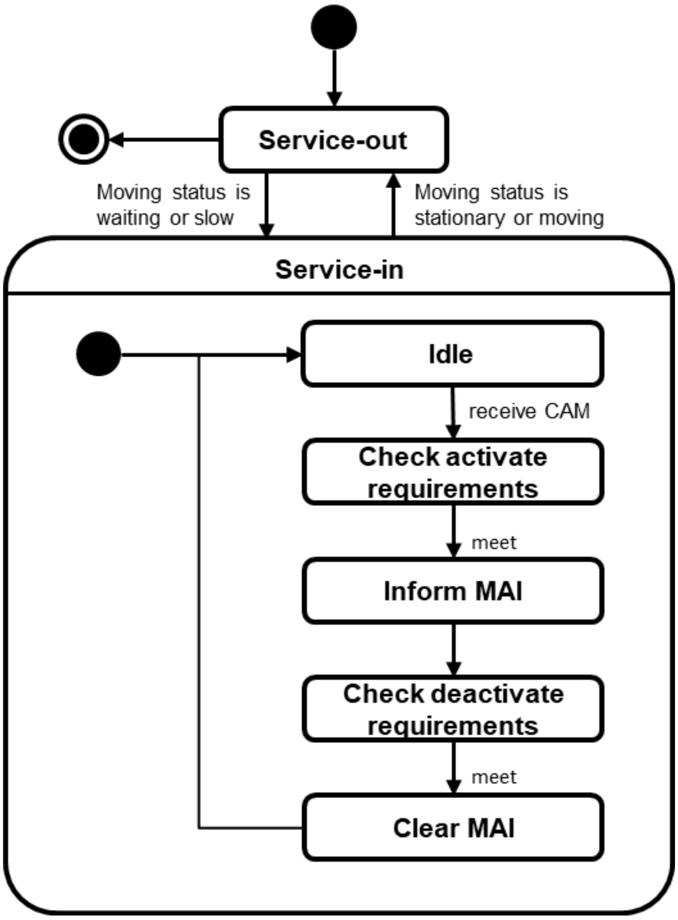


Figure A-3: State machine diagram of the MAI

A.3.1.2 Preconditions

The following are the preconditions for Perspective P3. All these preconditions must be satisfied in order for the service of the MAI application to be activated.

Table A-1: Preconditions of the Ego vehicle (Perspective P3)

#	Item	Condition
PC_1	Ego-vehicle type	Four wheeled vehicle
PC_2	Speed range	Less than 30 km/h
PC_3	Location	Any (Assuming intersections)
PC_4	Road type	Any (Assuming non priority roads)

<table>
<tr><td>PC_5</td><td>Time</td><td colspan="3">Any</td></tr>
<tr><td>PC_6</td><td>Weather</td><td colspan="3">Any</td></tr>
<tr><td rowspan="6">PC_7</td><td rowspan="6">Other conditions</td><td colspan="3">When the moving status of the ego vehicle that is classified by the following conditions of the ego vehicle is set to “Waiting” or “Slow”.</td></tr>
<tr><th>Moving status</th><th>Speed [km/h]</th><th>Gear and Braking condition</th></tr>
<tr><td>Stationary</td><td>v = 0</td><td>Parking or Parking brake ON</td></tr>
<tr><td>Waiting</td><td>0≤ v ≤10</td><td>Foot brake ON</td></tr>
<tr><td>Slow</td><td>0≤ v ≤20</td><td>-</td></tr>
<tr><td>Moving</td><td>20 < v</td><td>-</td></tr>
<tr><td>PC_8</td><td>Out of scope</td><td colspan="3">None</td></tr>
</table>

A.3.1.3 Activation and deactivation requirements

The activating and deactivating indicating requirements of the MAI application are stated below. Activate the indicating scheme when all of the conditions below are satisfied.

Table A-2: Activating conditions of MAI (Perspective P3)

<table>
<tr><th>#</th><th>Item</th><th>Condition</th><th colspan="2">Used data</th></tr>
<tr><td rowspan="6">AC_1</td><td rowspan="6">PTW CAM</td><td rowspan="6">C-ITS service shall be received at least one series of CAM that has the following data elements to detect the vehicle as a target PTW and calculate collision risk.</td><th>Data field</th><th>Value</th></tr>
<tr><td>StationType</td><td>A station type of ITS-S to limit the target to PTW.</td></tr>
<tr><td>Speed</td><td>A speed value of a target PTW.</td></tr>
<tr><td>Heading</td><td>A heading of a target PTW in a WGS84 coordinates system.</td></tr>
<tr><td>ReferencePosition</td><td>The geographical position of a target PTW.</td></tr>
<tr><td>ExteriorLights</td><td>A status of the exterior light switches of a target PTW.</td></tr>
<tr><td>AC_2</td><td>Calculate relative distance</td><td>This distance is the relative distance calculated from the position of ego vehicle and the position of target PTW obtained from the received CAM.
This relative distance shall be calculated continuously</td><td colspan="2">Ego vehicle: ReferencePosition
Target PTW: ReferencePosition</td></tr>
</table>

		while receiving CAM of PTW.	
AC_3	Calculate critical time	The critical time shall be calculated from the changing rate of relative distance as the formula below. $critical\ time\ [s] = \frac{d}{\Delta d/\Delta t}$ $\Delta\mathrm{d}/\Delta\mathrm{t}$*: Relative speed between vehicles* This critical time shall be calculated continuously while receiving CAM of target PTW.	Relative distance Ego vehicle: reference position Target PTW: reference position
AC_4	Determine collision risk	C-ITS service shall determine that there is a risk of collision with the target PTW when the calculated critical time is less than 5.5 s.	Critical time

Deactivate the indicating scheme when the condition below (DC_1) is satisfied.

Table A-3: Deactivating conditions of MAI (Perspective P3)

#	**Item**	**Condition**	**Used data**
DC_1	Disappear collision risk	C-ITS service shall determine that there is no risk of collision with the target PTW when the sign of calculated critical time is inversed after the PTW passes through the ego vehicle.	Critical time

A.3.1.4 Expected behaviour of indicating scheme

The following are the expected behaviour of indicating scheme. Classifies the type of collision and the direction of the oncoming PTW and helps to output information to the HMI.

Table A-4: Indicating scheme of MAI (Perspective P3)

<table>
<tr><th>#</th><th>Item</th><th>Condition</th><th>Used data</th></tr>
<tr><td>EB_1</td><td>Target PTW in vicinity</td><td>PTWs should subject to MAI are limited to them into 300 m around the ego vehicle in order to reduce calculation load.</td><td>relative distance</td></tr>
<tr><td>EB_2</td><td>Relative position</td><td>The relative position of a target PTW from the ego vehicle should be classified into the following four categorized areas that are centred on the position of the ego vehicle.
<table>
<tr><th>Relative position of a target PTW [deg]</th><th>Categorized area</th></tr>
<tr><td>-15 < r < 15</td><td>Ahead area</td></tr>
<tr><td>15 ≤ r ≤ 165</td><td>Right area</td></tr>
<tr><td>r ≤ -15 AND r ≥ -165</td><td>Left area</td></tr>
<tr><td>r < -165 OR r > 165</td><td>Behind area</td></tr>
</table></td><td>Ego vehicle: reference position, heading
Target PTW: reference position</td></tr>
<tr><td>EB_3</td><td>Relative direction</td><td>The relative direction should show the oncoming direction of the target PTW with the origin of the ego vehicle. The calculation formula is as follows.

Relative direction: rd [deg] = target PTW heading [deg] - ego vehicle heading [deg]</td><td>Ego vehicle: heading
Target PTW: heading</td></tr>
<tr><td>EB_4</td><td>Collision type</td><td>The collision type is used to determine collision with the oncoming PTW and can help display its situation on the HMI. This is classified from the above relative position and relative directions as follows.
<table>
<tr><th>Categorized area with target PTW</th><th>Relative direction of target PTW</th><th>Collision type for target PTW</th></tr>
<tr><td>Ahead area</td><td>rd < -90 or rd > 90</td><td>Left turn</td></tr>
<tr><td>Right area</td><td>-180 < rd < 0</td><td>Crossing right</td></tr>
<tr><td>Left area</td><td>0 < rd < 180</td><td>Crossing left</td></tr>
<tr><td>Behind area</td><td>-90 < rd < 90</td><td>Right turn</td></tr>
</table></td><td>Relative position
Relative direction</td></tr>
</table>

Appendix B Intersection Movement Assist (IMA)

B.1 Conception and Specification

B.1.1 Description

The Intersection Movement Assist (IMA) is a V2X-application which is able to warn the driver of a vehicle or PTW when it is not safe to enter an intersection due to a high probability of collision with other vehicles.
This application uses the vehicle data and the CAMs being sent by vehicles in its vicinity for computing the probability of a collision at an intersection. If necessary, this information is then given to the HMI, which in turn issues a notification or warning to the end-user in order to reduce the risk of a collision. The working environment of this application are intersections at which the paths of the Ego-vehicle and the Other-vehicle cross each other.

B.1.2 Concept of Notifications and Warnings

IMA requires the implementation of at least two information levels: notification and warning. shows a timeline illustrating the issue of information through the HMI before a collision occurs.

In this context, notifications are conceived to be given earlier as warnings and should lead to an increment of attention from the end-user. A warning, in contrast, should bring the end-user to perform an evasive manoeuvre in order to avoid the collision, i.e. brake and/or steer.

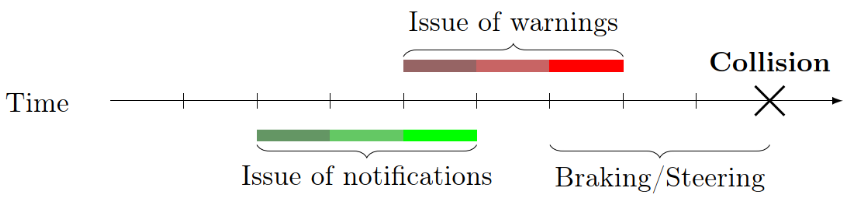


Figure B-1: Timeline for notifications and warnings

The coloured rectangles correspond to different possible timings for issuing a notification or warning. Both notifications and warnings should be issued early enough, so that the end-user has enough time for avoiding the accident; this includes the perception of the notification or warning and the appropriate reaction, i.e. braking and/or steering.

At best, a notification would be enough for neutralising the situation, so that the collision is avoided without a warning needed to be given. But if that is not the case, the driver would also receive a warning, and in order to avoid overwhelming the driver with notifications promptly followed by a warning, a minimum separation of 1.5s between those should be maintained[5].

[5] Arthur Werle, “Optimierung von Fahrerwarnungen mittels Probandenversuchen am Motorrad-Simulator,” Master’s thesis, Technische Universität Berlin, 3 2020.

B.1.3 Requirements

In order to work properly, be robust and achieve a suitable level of acceptance, IMA must be able to fulfill several requirements. This section deals with the different categories of requirements to be fulfilled by this application. A summary of those is presented in Table B-1.

Table B-1: summary of requirements to be met by the application IMA.

Needs	Requirements
IMA needs to know when a collision at an intersection involving the Ego-vehicle is about to take place.	IMA shall locally acquire location and motion parameters of the Ego-vehicle, in order to compute the risk of a collision.
	IMA shall acquire location and motion parameters of the Other-vehicle through CAMs, in order to compute the risk of a collision.
IMA needs to make sure that the information coming from other entities is valid and relevant, before using it for issuing notifications or warnings.	IMA shall verify that every received CAM contains a valid certificate or that it was sent by an entity with an already known certificate.
	IMA shall control that the received CAMs fulfill a series of prerequisites before proceeding to the risk computation.
IMA needs to detect when components of the system fail.	IMA shall notify end-user, via the HMI, in case the application is not working properly.
IMA needs to detect and inform about critical situations, giving the end-user the possibility of avoiding them.	IMA shall process incoming messages and issue information to the end-user, if necessary, within a given time-frame.
	IMA shall provide notifications and warnings to the end-user over a HMI.

B.1.3.1 Activation Requirements

The application IMA is not conceived for being constantly active, but for computing the probability of a collision only after some prerequisites are met. This measure exclude scenarios and situations, which would not lead to the issue of a notification or warning, thus sparing computation resources and time.

Speed range

The speed of the Ego-vehicle should be equal or lower than 100 km/h, as this is the highest speed allowed in rural areas, according to German traffic regulations (§3 Par. 3 of StVO). The speed limit for rural roads in other EU Member States also lies under this threshold[6].

Location

An intersection or junction is located ahead of the Ego-vehicle and the current road type does not correspond to a motorway with a speed limit above 100 km/h. This is only applicable when map data is available.

Driving direction

The headings of the Ego-vehicle and Other-vehicle indicate that they are approaching to each other and that their trajectories cross each other at an intersection[7].

Distance to Other-vehicle

Only the CAMs from entities closer than 300 m are to be considered[8,9]. This enables the detection of vehicles on time even when driving at a relatively high speed.

B.1.3.2 Real-time Requirements

One of the most important requirements for this application to fulfill are the real-time requirements, because of a warning issued too-late being useless or even distracting for the end-user. According to previous works, and in order for these kind of warnings to be effective, the Maximum Latency Time (MLT) of the system must satisfy the following[12]:

$$\text{MLT} \leq 200 \text{ ms}$$

[6] Mobility and Transport - European Commission, “Current speed limit policies.” https://ec.europa.eu/transport/road_safety/specialist/knowledge/speed/speed_limits/current_speed_limit_policies_en. based on studies made by consultants (accessed: 08.07.2020).

[7] When not using map data, and in order to consider the prerequisite as fulfilled, the trajectories must be found to cross each other transversely.

[8] For an intersecting angle of 90 degrees, the distance from the vehicles to the intersecting point corresponds to 212.13 meters, which is also be the minimum distance to the conflict area for at least one of the vehicles.

[9] ETSI, “Intersection Collision Risk Warning (ICRW), application requirements specification – ETSI TS 101 539-2,” tech. rep., ETSI, 6 2018.

[12] Florian Schellin, “Sensitivitätsanalyse eines AS-Systems unter Berücksichtigung von V2X- Kommunikation zur Vermeidung von Ausgewählten PKW-KRAD-Unfällen,” Master’s thesis, Tech- nische Universität Berlin, 3 2018.

The MLT describes the time for processing the received V2X-messages, i.e. the total time for computing the risk of a collision, and the issue of information to the end-user over the HMI[13]. This MLT can be described as the sum of the following components:

$$\text{MLT} = t_{VehicleData} + t_{Cert} + t_{Risk} + t_{HMI}$$

- Time for gathering information related to the current state of the Ego-vehicle ($t_{VehicleData}$): this includes reading data from the CAN-Bus, the LIN-Bus and the GNSS-receiver. This information is to be collected when generated instead of being gathered upon request. Which leads to low latency times (« 1 ms), as up-to-date information would be already stored in the local memory of the Controller Device.

- Time for validating the digital certificate of the received CAM (t_{Cert}): according to the performance of commercial-available hardware[14], the following validation times can be expected for the indicated elliptic curves:

$$t_{Cert} = \begin{cases} \sim 0 \text{ ms if Certificate already known}^{15}; \\ 0{:}43 \text{ ms if ECDSA\_NIST\_P256 is used;} \\ 2{:}56 \text{ ms if ECDSA\_NIST\_P384 is used;} \\ 1{:}37 \text{ ms if ECDSA\_Brainpool\_P256 is used;} \\ 3{:}33 \text{ ms if ECDSA\_Brainpool\_P384 is used:} \end{cases}$$

- Time for estimating the collision risk (t_{Risk}): during this time, the application uses the previously gathered information for estimating the probability of a collision. If map data is available, this also includes obtaining the intersection attributes from the corresponding database.

- Time for presenting warning over HMI (t_{HMI}): this is the delay between the application having informed the system about the need of a notification or warning and the information being presented to the end-user. This delay strongly depends on the implementation of the HMI, but is usually located in the lower millisecond-range.

The application must also be able to process at least 1000 V2X-messages per second[16], which realistically corresponds to the maximum number of messages which can be received by a road entity within one second. This maximum number of messages per second is based on the time needed for the transmission through the physical channel and is bound to the

[13] MLT can also refer to the time until an automated response is initiated by the vehicle.

[14] Autotalks, CRATON2/SECTON Security - Application Note, 2019. Rev. 1.1.

[15] As the same certificate is used as long as the pseudonym does not change, it can be verified only the first time and then stored as such in local memory in order to avoid the need for verifying it again.

[16] ETSI, “Intersection Collision Risk Warning (ICRW), application requirements specification – ETSI TS 101 539-2,” tech. rep., ETSI, 6 2018.

communication technology being used. In the case of the C-V2X technology, a sub-frame for the transmission of a whole message lasts 1 ms.

This means that in order for the application to consider all incoming information, it must be able to process CAMs with time

$$t_{Risk} < 1\,\mathrm{ms}$$

B.1.3.3 Reliability Requirements

The reliability of the application can be divided into two main aspects: the first one is the reliability of the information given, i.e. how accurate is the algorithm at detecting collisions, while the second one refers to the level of fault-tolerance of the system.

Regarding the reliability of the information given, the application should aim to minimize the below-mentioned factors:

- False positives (or false warnings), defined as the warnings given in non-critical situations.
- False negatives (or missed warnings), defined as the critical situations for which no warning is given.

Those factors can be used for describing the performance of the collision-detection algorithm and their minimization leads to an increase in acceptance from the end-user[17]. A list with all the performance indicators used in this work is found in B.2.3.

Regarding the aspect of fault-tolerance, the application must be able to detect when components fail or are offline. It should then enter a fail-silent mode and inform the end-user about this state. While in fail-silent mode, received V2X-messages are not processed and no notifications or warnings are given to the end-user.

The application could also perform a self-check while keeping an indicator light turned on until this self-check is finished, thus operating similar to the diagnostic self-check of Anti-lock Braking Systems on modern PTWs[18].

Such a self diagnostic should at least confirm that the following elements are working properly:

(a) Communication: the system is able to receive CAMs from another road entity.

(b) Security module: received CAMs can be validated.

(c) Bus system and sensors: all necessary vehicle data is available.

(d) Collision-detection algorithm: the probability of a collision can be computed.

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[17] M. Rahman, Driver acceptance of advanced driver assistance systems and semi-autonomous driving systems. PhD thesis, Mississippi State University, 2016.

[18] This system waits for the PTW to start moving, in order to check that all sensors are working properly. The indicator light remains consequently on, until these checks are done.

(e) Information output: communication with the HMI can be established.

B.1.3.4 Compatibility Requirements

The information contained in the received V2X-messages should comply with current standards[19,20]. And although the specification of this V2X-application is mostly based ETSI's standards, all data elements used by the algorithms in this work are to be found in both BSMs and CAMs, which makes possible using the same collision-detection algorithms for both standards.

B.1.4 Approaches

This section presents different approaches for the implementation of a collision-detection algorithm based on V2X-communication.

The following story-line describes a dangerous situation taking place at a road intersection, and will be used for illustrating how the different approaches work. As seen in Figure B-2, four different vehicles are located near to an intersection, three of them (EV-1, OV-1 and OV-2) are driving into the intersection while the fourth one (OV-3) is getting away from this.

Both OV-1 and OV-2 are driving into the intersection and have right-of-way over EV-1. OV-2 is driving at a relative low speed while OV-1 drives at an adequate speed for these road. EV-1 plans to cross the intersection and becomes aware of OV-2 and OV-3, but not of OV-1 because of OV-3 interrupting the Line-of-Sight between EV-1 and OV-1. Because of OV-2 driving slowly, EV-1 sees an opportunity for crossing the intersection. But as it tries to drive across the intersection, EV-1 collides with OV-1 and alleges not having seen OV-1 coming.

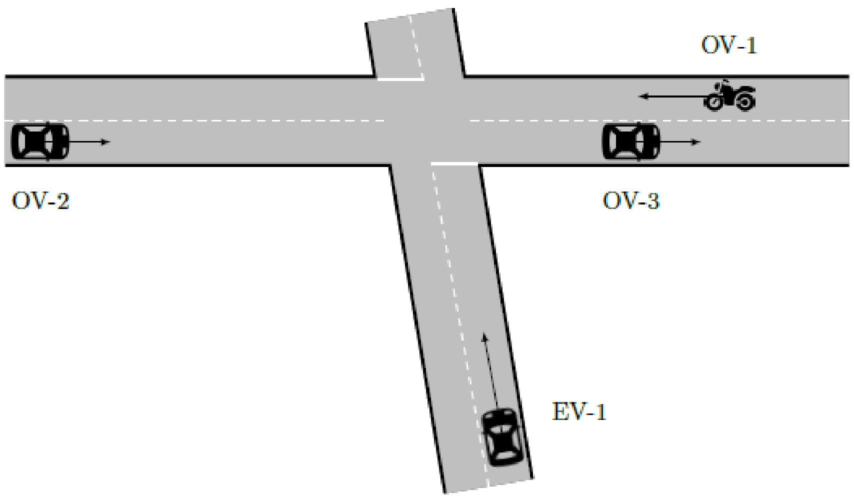

Figure B-2: Example of a dangerous situation at an intersection.
(EV corresponds to Ego-Vehicle and OV corresponds to Other-Vehicle)

This kind of situations can be avoided by using V2X-communication together with a collision-detection algorithm. The following subsections present different approaches for the implementation of such an algorithm. It is assumed that all vehicles involved in this scenario

[19] ETSI, "Applications and facilities layer, common data dictionary - ETSI TS 102 894-2," tech. rep., ETSI, 8 2018.

[20] SAE, "On-Board System Requirements for V2V Safety Communications (J2945/1_201603)," tech. rep., SAE, 3 2016.

are capable of broadcasting V2X-messages, and that only the Ego-Vehicle (EV-1) makes use of a collision-detection algorithm.

B.1.4.1 SAE-based

This approach is based on the document *J2945/1* from the Society of Automotive Engineers (SAE), which describes on-board system requirements for V2V safety communications[21]. It makes use of two relevant zones for the detection of vehicles which could pose a threat for the Ego-vehicle. Figure B-3 shows the above described situation under the implementation of this approach.

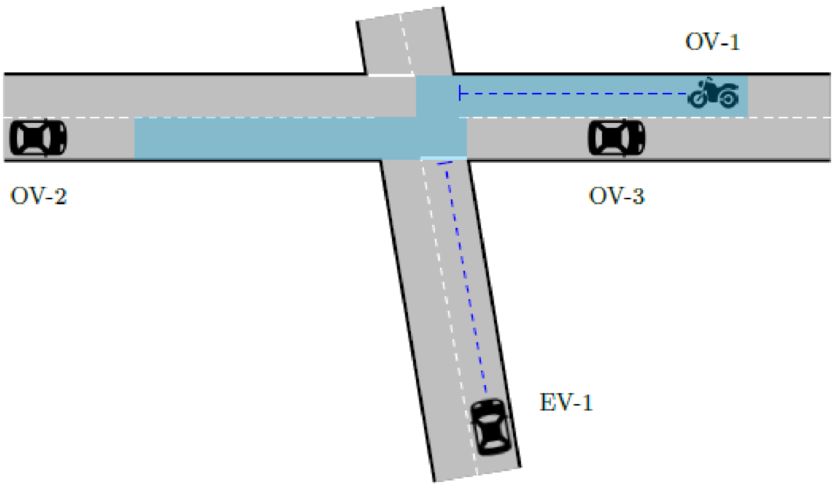

Figure B-3: Concept of collision detection at intersections proposed by SAE.

(The blue rectangles represent the relevant zones to be monitored by the application. The blue, dashed lines represent the Time to Intersection (TTI) and Distance to Intersection (DTI) for EV-1 and OV-1.)

Two relevant zones are projected into the road and the vehicles inside of them are taken into consideration for computing the collision risk. Vehicles inside of these zones are then near enough to the intersection ahead of the Ego-vehicle, and also driving towards this intersection, because of the covered lanes corresponding to lanes going into the intersection. As appreciated in Figure B-3, only one of the three OVs is inside a relevant zone. This is because of OV-3 having passed the intersection and OV-2 still being too far away from it.

In order to avoid the collision between EV-1 and OV-1, this approach would compute the probability of them being inside the intersection at the same time. For doing this, a Time to Intersection (TTI) and a Distance to Intersection (DTI) is computed for every vehicle inside of a relevant zone and then contrasted with the TTI and DTI of the Ego-vehicle in order to estimate the risk of a collision and give a warning, if needed.

B.1.4.2 ETSI-based

This approach is based on the document *ETSI TS 101 539-2* from the European Telecommunications Standards Institute (ETSI)[22]. This approach utilizes the concepts of Time

[21] SAE, “On-Board System Requirements for V2V Safety Communications (J2945/1_201603),” tech. rep., SAE, 3 2016.
[22] ETSI, “Intersection Collision Risk Warning (ICRW), application requirements specification – ETSI TS 101 539-2,” tech. rep., ETSI, 6 2018.

to Collision (TTC) and Dynamic Safety Shield (DSS) for detecting potential collisions. This concept is depicted in Figure B-4.

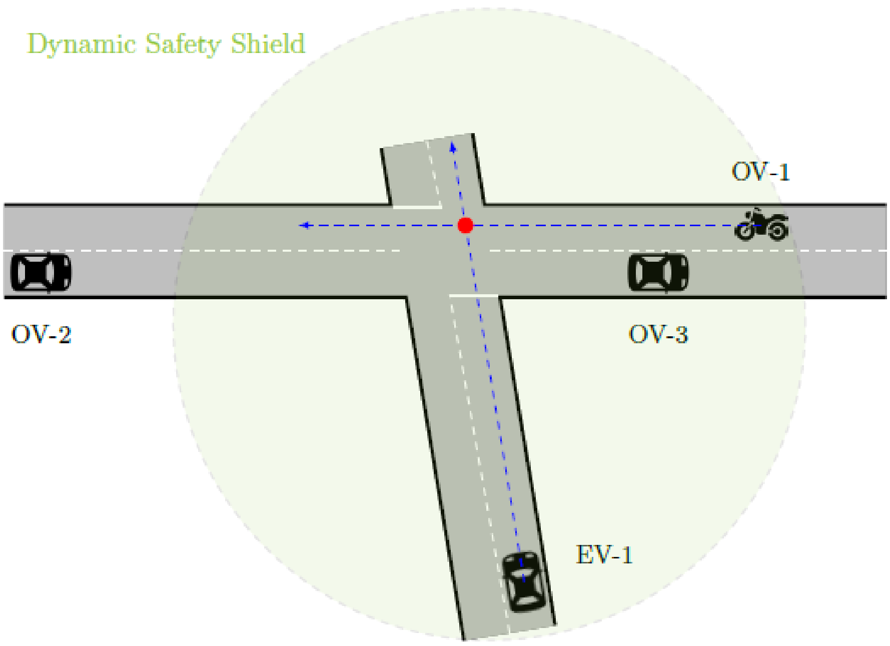

Figure B-4: Concept of collision detection at intersections proposed by ETSI.

(The blue, dashed lines represent the trajectories to be followed by the vehicles and the red point is the intersection of those trajectories, representing the Point of Collision.)

The DSS is a virtual area surrounding the Ego-vehicle. The form of this shield is flexible and all vehicles inside of it are considered relevant for the collision-detection algorithm. The TTC is the time for a vehicle to reach the estimated Point-of-Collision under constant driving conditions. In order to trigger a warning, this parameter should be below a threshold TTC_{min}, which indicates the time left for the driver to take an action and is specified as follows:

$$TTC_{min} > MLT + MDRT + MAT + \varepsilon$$

In this equation, the MLT denotes the maximum delay allowed when issuing a warning (See B.1.3.2), the Maximum Driver Reaction Time (MDRT) denotes the time elapsed between the warning being given and the driver taking an action, and the Maximum Action Time (MAT) indicates the time needed for a collision-avoidance action, e.g. the time for the vehicle to stop. For taking the error of the sensors into consideration, a time margin ε is added to the equation.

Under this approach, and in order to avoid the collision between EV-1 and OV-1, a Point of Collision (PoC) is calculated by using the driving trajectories of the vehicles inside the DSS. If there is no Point-of-Collision, as in the case of OV-3, the vehicle is not further considered by the algorithm. The obtained Point-of-Collisions are then used for estimating the TTC of every vehicle. A warning is given when both TTCs are similar, i.e. both vehicles are to reach the Point-of-Collision at approximately the same time, and the following holds for the Ego-vehicle:

$$TTC \leq TTC_{min}$$

B.1.4.3 ETSI-based with Map Data

This approach is based on the concept mentioned above, with the difference of having access to map data. By using this data, the algorithm can filter out areas which are not of interest for the application, e.g. parking lots, roundabouts, off-road, etc.

When using this approach, the trajectories of EV-1 and OV-1 are not needed for calculating the Point-of-Collision. This point is instead obtained by getting information about the position of the intersection and the lanes, on which the vehicles are currently driving. This Point-of-Collision is then used for the calculation of the TTCs needed for estimating the risk of a collision.

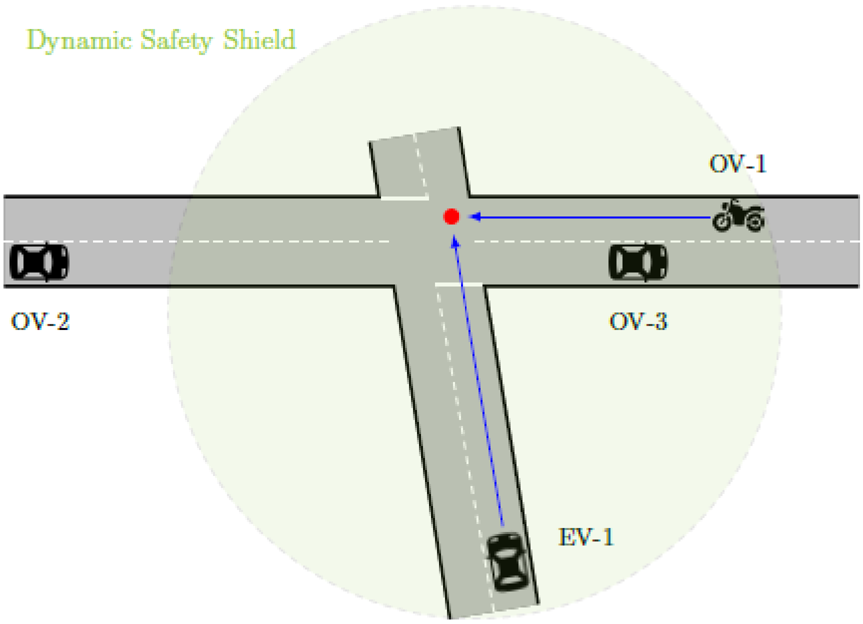

Figure B-5: Map-assisted collision detection based on ETSI's concept.

(The red point represents the Point-of-Collision, while the blue arrows correspond to the time and distance to be covered by the vehicles in order to get to the Point-of-Collision.)

B.1.4.4 Ghost Vehicles

This is an *a-posteriori* approach based on the idea of predicting the future position of the vehicles and then assessing if they overlap, which in turn indicates that a collision is to take place. An illustration of this concept is found in Figure B-6: Concept of collision detection based on ghost vehicles.. It shows multiple ghost vehicles representing the predicted position of every real vehicle.

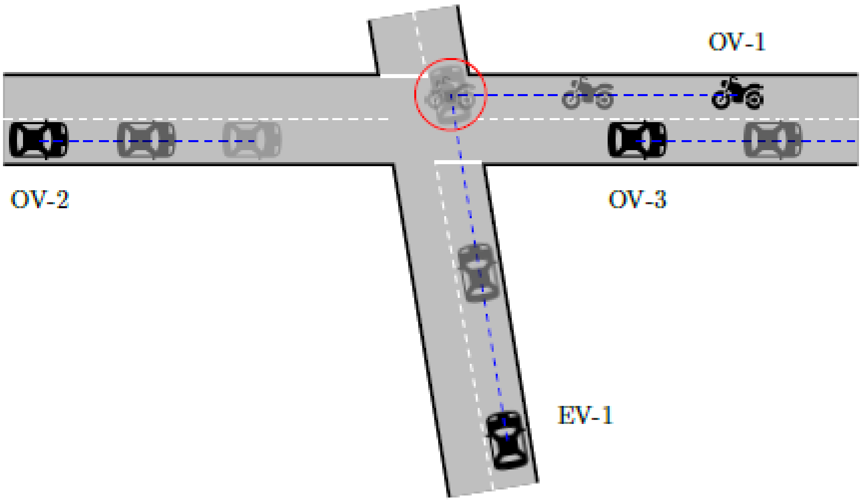

Figure B-6: Concept of collision detection based on ghost vehicles.

(The semitransparent vehicles represent the ghost vehicles. Their level of transparency indicates how far into the future they are predicted. The red circle highlights the intersection between two ghost vehicles, which indicates that a collision is about to happen.)

The future position of every vehicles is estimated according to its current driving state, i.e. position, speed, acceleration, etc., assuming a constant driving conditions and extending this driving state over a fixed amount of time. And every time, after the ghost vehicles are generated, the algorithm searches for overlaps between pairs of ghost vehicles by measuring the intersected area or the distance between the ghost vehicles.

For avoiding the collision between EV-1 and OV-1, this approach generates ghost vehicles for all vehicles in the vicinity of EV-1[23] and proceeds to measure the overlap between the generated ghost vehicles. If this overlap is found to be above a certain threshold, a warning is given.

[23] This approach does not make use of relevant zones or Dynamic Safety Shields, although those techniques could also be implemented for avoiding generating unnecessary ghost vehicles, e.g. for OV-3.

B.2 Evaluation

This section offers a theoretical and empirical analysis on the performance of the implementation of the four different approaches. It begins with generation of the data set used for the evaluation of the algorithms and the selected models for recreating the driver reaction upon reception of a warning. It continues explaining the different indicators used for assessing the performance of the approaches and then presents the results of simulation and driving trials, thus providing an insight into the capabilities and potential of every approach.

B.2.1 Data Set

The data set created for this evaluation can be divided into categories, which are composed by several scenarios and intend to test distinct properties of the different approaches.

The classification used for the reconstruction of accidents in Germany is taken as a reference for the construction of the scenarios for this evaluation[24]. This classification distinguishes between 7 different types of accidents, each one describing the properties of the road, the kind of users involved (e.g. vehicle, pedestrian, cyclist), their initial position with respect to each other and the maneuver they perform (e.g. turning left, turning right, going straight).

The two relevant types of accidents for this work are Type 2 and Type 3, which describe accidents between at least two vehicles taking place at intersections:

- **Accidents while turning (Type 2):** this type stands for accidents between two vehicles which drive in the same or in opposite directions. The oncoming-traffic scenarios belong to this category and represent the uses cases for LTA.
- **Accidents while crossing or merging (Type 3)**: this represents accidents taking place at a crossing or T-junction and in which the vehicles drive in non-parallel directions, thus corresponding to the use cases for IMA.

Some of the accident codes contained in each accident type are group together because of each one of these accident types covering several kinds of situations while only some of these situations are of relevance for the applications IMA and LTA. Table B-2 shows the accident codes of the different situations. The details of the clustering made for this evaluation can be found in Table B-3.

[24] Gesamtverband der Deutschen Versicherungswirtschaft e. V. , “Unfalltypen-Katalog.” https://udv.de/sites/default/files/tx_udvpublications/unfalltypen-katalog_udv_web_2.pdf, 1 2016.

Table B-2: Accident codes used for evaluation.

Scenario	Code	EV	OV
Oncoming-traffic (LTA)	211	↰	↑
	212	↰	↱
	215	↰	↰
	351	↑	↰
Cross-traffic OV from left (IMA)	301	↑	↑
	302	↰	↑
	303	↱	↑
	306*	↰	↱
	326*	↱	↱
Cross-traffic OV from right (IMA)	321	↑	↑
	322	↰	↑
	323*	↱	↑

(Columns EV and OV corresponds to the action taken by the Ego-vehicle and Other-vehicle, respectively. A star next to a code indicates that this scenario does not lead to a collision under normal driving conditions, e.g. both vehicles turning left in front of each other.)

Table B-3: Clustering of accident codes in different categories of scenarios

Application (Situation)	Maneuver	Accident codes
IMA (OV comes from left)	EV driving straight	301, 311
	EV turning lef	302, 312, 261
	EV turning right	303, 313
IMA (OV comes from right)	EV driving straight	321, 331, 355, 353, 271
	EV turning left	322, 332, 352
	EV turning right	323, 333
LTA (EV turns left)	OV driving straight	211, 281, 354
	OV turning right	212
	OV turning left	215

The selected accident codes are used for populating the following categories of scenarios:

- **Collision**: scenarios at which a collision does take place. These scenarios are used for testing the collision-detection properties of every approach, as they enable the estimation of collisions predicted in-time, too late or not at all.
- **No-collision**: scenarios at which a collision could occur but does not occur. Those scenarios test the fine-tuning of the approaches by confronting them with situations which could appear to be critical, but does not end in a collision, thus testing their tendency of giving false warnings.
- **Safe**: scenarios at which no collision can occur. On these scenarios, the trajectories of the

vehicles do not intersect each other, which allows for testing the robustness of the approaches when a collision is not likely.

Although the accident codes in the category *Safe* are found only in this category, the scenarios of both *Safe* and *No-collision* are used for the estimation of false warnings.

Generation of Scenarios

Having the starting position and maneuvers of the vehicles, which are prescribed by the accident code, the corresponding scenarios can be generated.

In order to make the scenarios as representative as possible, the speed values for the scenarios are chosen according to the cumulative distribution of speed in zones with different speed limits. According to the bar graph presented in Figure B-7, the number of relevant zones amounts to three: 30 km/h, 50 km/h and 80 km/h zones[25]. This graph also indicates the amount of scenarios to be generated for every speed zone.

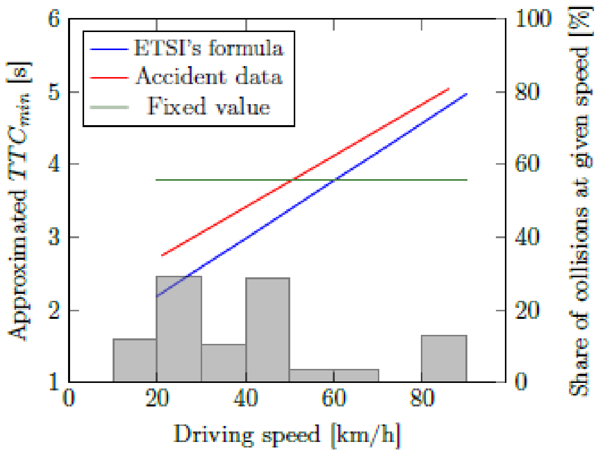

Figure B-7: Approximation of TTC_{min} based on different methods.

(The x-axis represents the driving speed of the Ego-vehicle, the y-axis on the left corresponds to the threshold value calculated using the indicated methods and the y-axis on the right shows the percentage of registered collision accidents having the speed on the x-axis as the initial speed, i.e. the driving speed before trying to avoid the collision. The highest shares on this bar graph correspond to three different groups of locations: 30km=h zones, 50km=h zones and rural areas.)

The cumulative functions corresponding to the 30 km/h and 50 km/h speed distributions are derived[26], while the distribution for 80 km/h is estimated based on the first two. The resulting speed distributions are shown in Figure B-8.

[25] The 80km/h zone corresponds to the driving speed at crossings and T-junctions on rural areas.

[26] Hagen Schüller, "Modelle zur Beschreibung des Geschwindigkeitsverhaltens auf Stadtstraßen unddessen Auswirkungen auf die Verkehrssicherheit auf Grundlage der Straßengestaltung ." https://tu-dresden.de/bu/verkehr/ivs/vnm/ressourcen/dateien/institutsschriftenreihe/Heft-12.pdf, 12 2010.

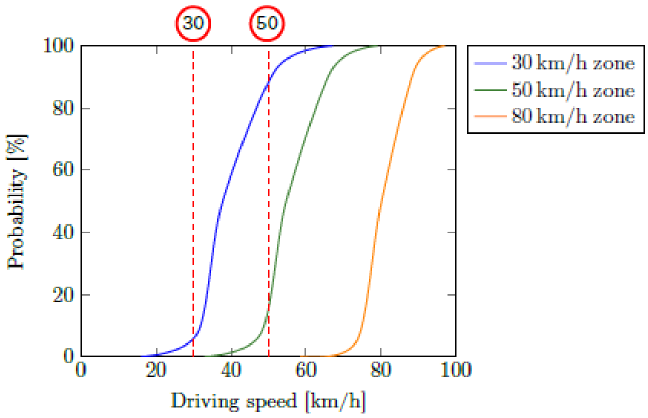

Figure B-8: Driving speeds in zones with different speed limits.

(Cumulative distribution function for driving speeds inside of 30 km/h, 50 km/h and 80 km/h zones.)

All three distributions rely on the concept of v_{85}-speed, which describes the driving speed for 85 % of the road users. Those were obtained from sensor measurements in different locations and used for generating v85-speed ranges corresponding to the different zones[27].

B.2.2 Driver Model for Warning Reactions

Not all drivers react the same way when confronted with a dangerous road situation, and in order to test the different approaches against different human responses, a driver model for warning reactions is implemented. The human responses in dangerous road situations can be classified according to two different factors:

- **Reaction time:** this is the time a driver needs between receiving an information and taking a certain evasive action, e.g. perform an emergency brake.
- **Breaking intensity**: this refers to how intensively a driver brakes. For this evaluation, and in order to cover different road and tire conditions, intervention of ABS and cohesion coefficients, the maximum possible deceleration[28,29] (intensity of 100%) is set to 7 m/s^2.

In this work, six different models for simulating driver reactions upon reception of a warning are used. Those were estimated[30] by combining the three most probable reaction times with two observed braking intensities, a strong one and weak one. The resulting models and their probability of occurrence are presented in Table B-4.

[27] The v85-speeds for 30km/h and 50km/h zones cover the ranges 31-52km/h and 48-67km/h respectively.

[28] The deceleration of a vehicle in good technical condition while braking on dry asphalt is in the range of 6.0–7:85m/s^2.

[29] N. Kudarauskas, "Analysis of emergency braking of a vehicle," Transport, vol. 22, 07 2007.

[30] simTD, "Simulation realer Verkehrsunfälle zur Bestimmung des Nutzens für ausgewählte simTDAnwendungsfälle auf Basis der GIDAS Wirkfeldanalyse," tech. rep., European Center for Information and Communication Technologies (EICT), 1 2013.

Table B-4: Reaction models according to their probability of occurrence.

Model	1	2	3	4	5	6
Reaction time	0.72 s	0.54 s	0.72 s	1.06 s	0.54 s	1.06 s
Braking intensity	100 %	100 %	50 %	100 %	50 %	50 %
Probability of occurrence	0.36	0.27	0.12	0.12	0.09	0.04

B.2.3 Performance Evaluation

The performance of the different approaches is primarily measured in terms of accidents avoided thanks to a warning, accidents not avoided due to non-detection and the rate of false warnings, i.e. warnings given during not-dangerous situations[31].

In order to evaluate these performances, every scenario is simulated at least twice. A first time without the intervention of the collision-avoidance algorithm, i.e. the algorithm remains disabled during the whole scenario, and a second time having the algorithm enabled. The first run serves the purpose of knowing the outcome of the scenario in advance, the scenario can then be classified into the previously introduced categories *Collision* or *No-collision*.

Performance indicators

For the evaluation of the different approaches, the following performance indicators are used:

(a) **Percentage of successfully avoided collisions**: this is the number of collisions that didn't happen in the simulation for which a warning is given and the total number of collisions occurred in the simulation when there is no intervention by the algorithm.

(b) **Percentage of too-late detected collisions**: this is the ratio between the number of collisions occurred in the simulation for which a warning is given and the total number of collisions occurred in the simulation when there is no intervention by the algorithm.

(c) **Percentage of not-detected collisions**: this is the ratio between collisions occurred in the simulation for which no warning is given and the total number of collisions occurred in the simulation when there is no intervention by the algorithm.

(d) **Percentage of true positives**: this is given by the ratio between the number of detected collisions (avoided or not) and the total number of collisions occurred in the simulation when there is no intervention by the algorithm. The number of detected collisions is the sum of (a) and (b).

(e) **Percentage of false positives**: this is defined as the percentage of non-dangerous situations for which a warning is given.

(f) **Percentage of false negatives**: this is equivalent to the percentage of not-detected collisions (c).

(g) **Percentage of true negatives**: this is defined as the complementary of the percentage false positives.

[31] Leonardo Lo Schiavo, "Performance of MEC Solutions in Automotive Applications," Master's thesis, Politecnico Di Torino, 10 2018.

B.2.4 Simulation Results

This section presents the results obtained through the simulation. In order to determine the strengths and weaknesses of the approaches for different scenarios, multiple speeds are generated stochastically for all accident codes. The total amount of scenarios used for the evaluation is shown in Table B-5.

Table B-5: Amount of scenarios for evaluation inside the simulation.

Category	Accident codes	Quantity	Total
Collision	8	24	192
No-collision	8	24	192
Safe	4	24	96
			480

All different approaches are confronted with the same test scenarios, i.e. the same sets of data, and executed using all six models for driver reaction. The results for the different driver models are weighted according to their probability of occurrence and combined in a single statistic.

B.2.4.1 SAE

The following graphs show the results obtained for the SAE-based approach under the different categories of scenarios.

Detection accuracy

Figure B-9 presents the results for the category *Collision*. For this category, three performance indicators are obtained and associated to the corresponding accident code as well as to the corresponding use cases, i.e. either IMA or LTA.

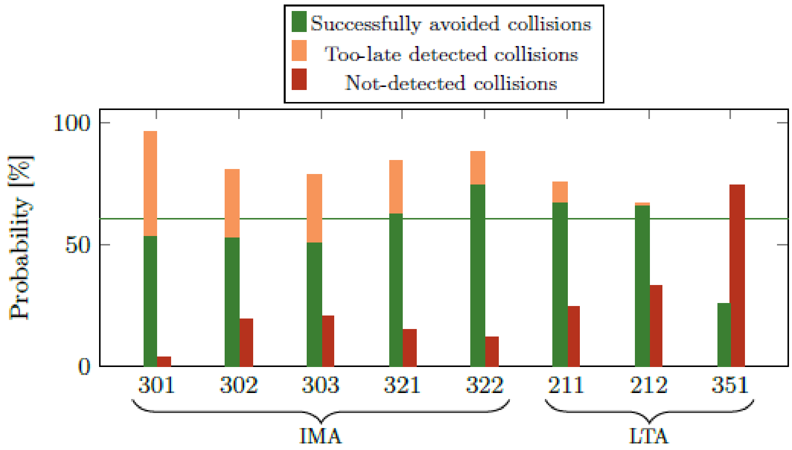

Figure B-9: Performance of SAE-based approach for Collision scenarios.

(Green line represents average performance when not covering accident code 351.)

Figure B-10: Performance of SAE-based approach for Collision scenarios.

(Green line represents average performance.)

Figure B-10 shows the results for the categories *No-Collision* and *Safe* together, as they are both used for the estimation of true negatives and false positives, i.e. false warnings.

Runtime

Figure B-11 then illustrates the runtime of the SAE-based algorithm for the three different possible outcomes, i.e. warning, notification and no-information. The runtime for every outcome is expressed in terms of the average time, the time corresponding to the 25th and 75th percentile, as well as the maximum and minimum time needed in order to estimate the risk after having the information about the properties of the intersection.

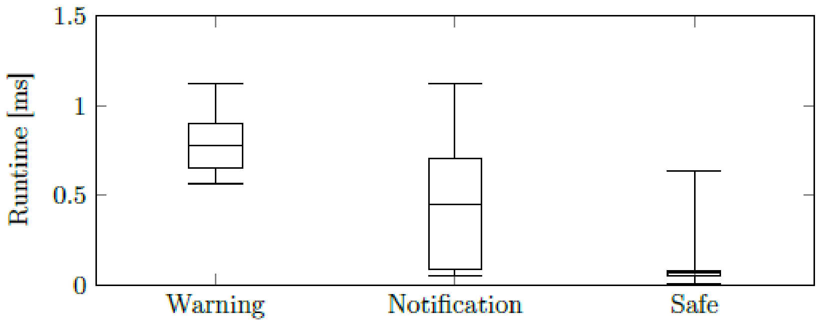

Figure B-11: Runtime of SAE-based algorithm.

Interpretation of results

This approach demonstrated being capable of avoiding over 60 % of the collisions, with only one scenario being well below the average, i.e. 351. This scenario corresponds to the use case "Other-vehicle turning left ahead" and is specially challenging because of the Ego-vehicle not knowing the Other-vehicle’s intention of turning left.

The average proportion of false negatives is below 25 %, with only two scenarios showing a high rate of false warnings, i.e. 215 and 306. Those scenarios correspond to the cases in which both vehicles turn left in front of each other and in which the Other-vehicle is approaching the Ego-vehicle from the left side and intends to turn right at the intersection. Just as for the scenario 351, the lack of information about the next maneuver of the Other-vehicle makes these scenarios challenging for the algorithm.

The runtime inside the simulation environment is constantly below the limit of 1 ms. The speed of computations for non-dangerous scenarios being relatively high in comparison to the other two. This is due to the relevant areas delimiting the area of interest and quickly ignoring vehicles outside of those.

B.2.4.2 ETSI

The simulation results obtained for this approach are presented in the same manner as the ones in the previous section.

Detection accuracy

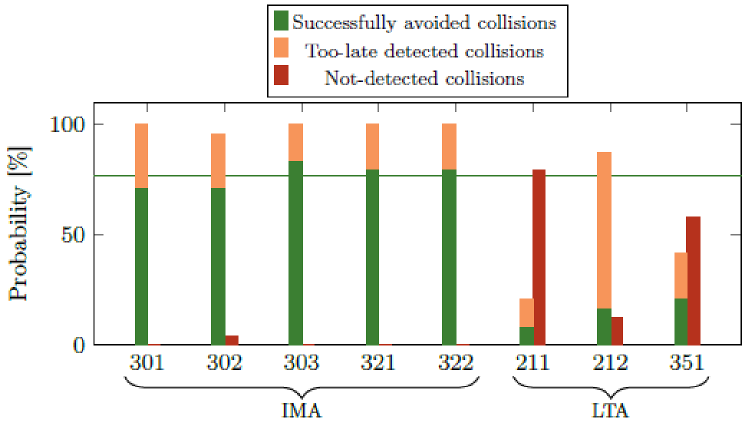

Figure B-12: Performance of ETSI-based approach for Collision scenarios.

(Green line represents average performance when not covering LTA use cases.)

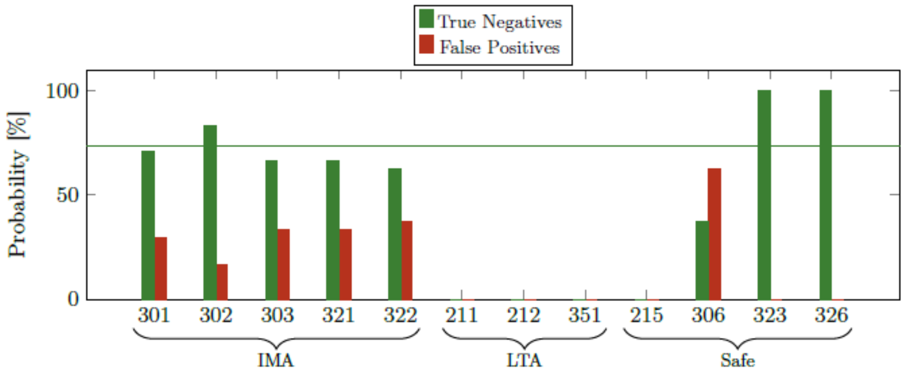

Figure B-13: Performance of ETSI-based approach for No-collision and Safe scenarios.

(Green line represents average performance. The LTA use cases, i.e. 211, 212, 351 and 215, are excluded because of this approach not being able to issue warnings under such circumstances.)

Runtime

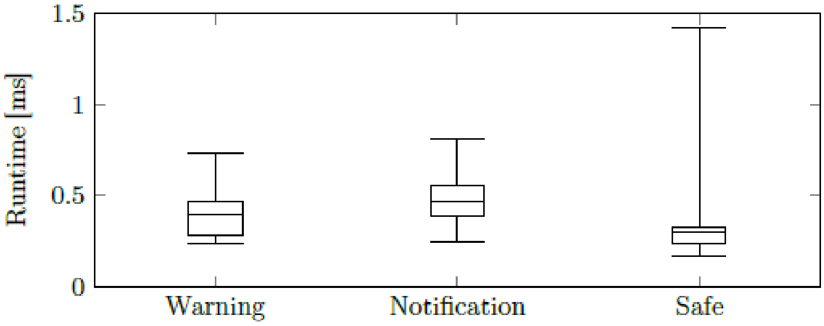

Figure B-14: Runtime of ETSI-based algorithm.

Interpretation of results and special considerations

It is noticed that the detection accuracy of this approach is sufficient for issuing LTA-notifications but not for giving LTA-warnings. This due to the turning point of the Ego-vehicle being unknown to the algorithm. The runtimes for both warnings and notifications are similar, because of the algorithm performing the same computations for both of them. The time for assessing non-dangerous situations varies greatly in some cases due to the need of solving triangle equations before classifying them as non-dangerous.

Figure B-15: ETSI-based approach estimating a Point-of-Collision out of the road.

(Because of the lack of map data, the ETSI-based approach does not distinguish between intersections and curves. This could lead to the calculation of unreachable Point-of-Collisions when two vehicles approach a curve.)

An important aspect to be considered for this algorithm are the false warnings taking place outside of intersections. The lack of map data could lead to the estimation of a Point-of-Collision located outside of an intersection, which in turn leads to possible false warnings. This is illustrated in Figure B-15.

B.2.4.3 ETSI with map data

Below are the result for the ETSI-based approach using map data for estimating the location of the Point of Collision.

Detection accuracy

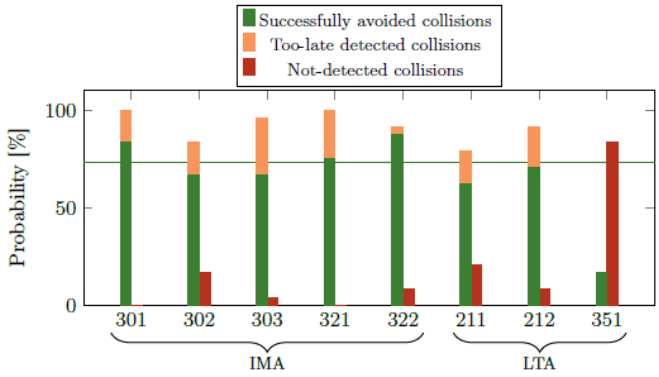

Figure B-16: Performance of ETSI-Map approach for Collision scenarios.

(Green line represents average performance.)

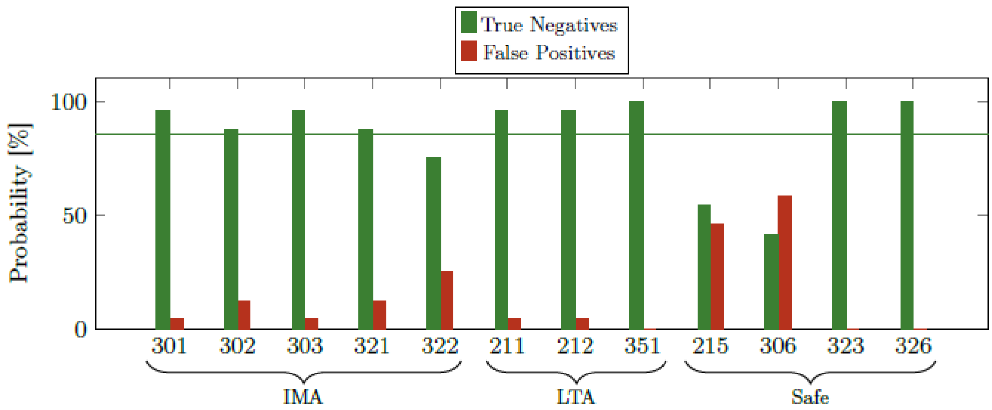

Figure B-17: Performance of ETSI-Map approach for No-collision and Safe scenarios.

(Green line represents average performance.)

Runtime

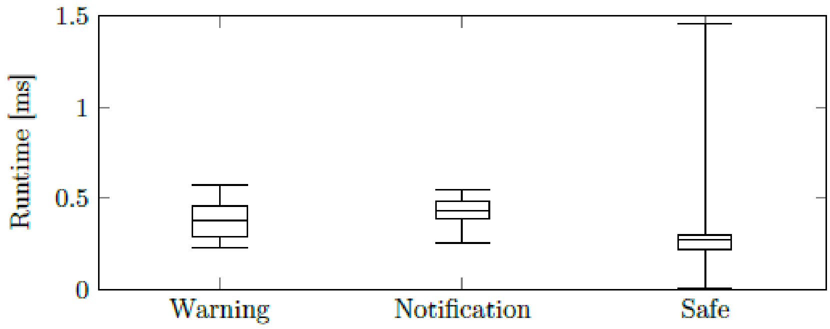

Figure B-18: Runtime of ETSI-Map algorithm.

Interpretation of results

In contrast to its parent approach, this one demonstrates a certain ability to avoid collisions in LTA use cases. This is due to the additional information about the location of the intersection, which is used for estimating the possibles Point of Collisions.

This approach, similar to the SAE-based approach, tends to give false warnings for the scenarios 215 and 306, as well as not giving any warnings for the scenario 351. This is largely due to the lack of information about the maneuver the Other-vehicle is about to perform.

The estimated runtimes are similar to the ones of the ETSI-based approach. This is primarily due to both approaches calculating the TTC and evaluating the risk of a collision in the same manner.

B.2.4.4 Ghost Vehicles

This subsection presents the results for the approach based on the prediction of the vehicle's position, i.e. the generation of ghost vehicles. The algorithm for this approach is evaluated using d_{min} = 3.7 m (the distance between two ghost vehicles when a warning is given).

Detection accuracy

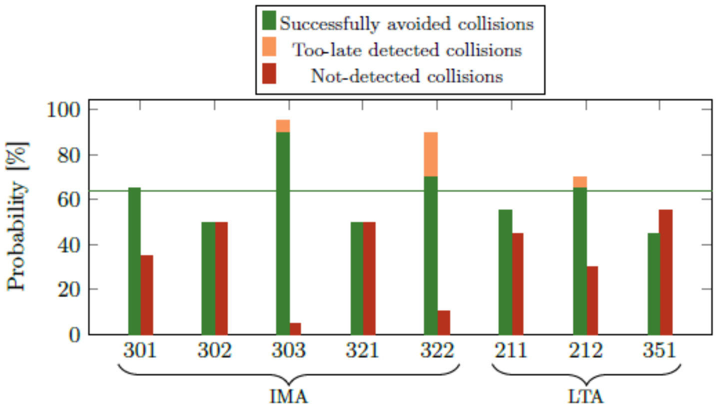

Figure B-19: Performance of approach based on ghost vehicles for Collision scenarios.

(Green line represents average performance of this algorithm.)

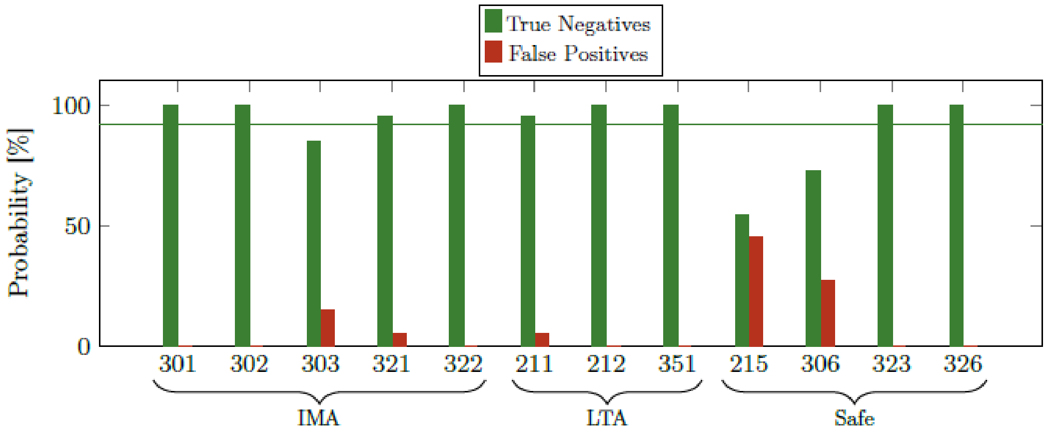

Figure B-20: Performance of approach based on ghost vehicles for No-collision and Safe scenarios.

(Green line represents average performance.)

Runtime

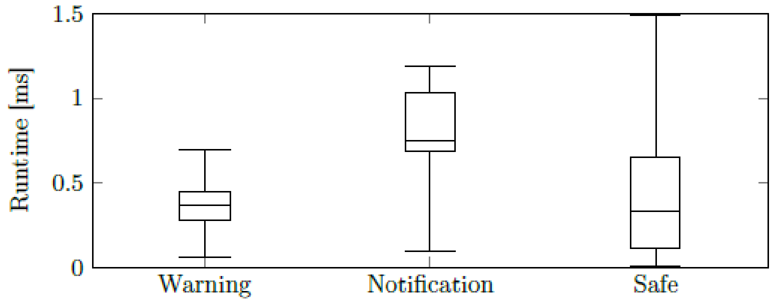

Figure B-21: Runtime of algorithm based on ghost vehicles.

Interpretation of results and special considerations

In contrast to other approaches, only a small amount of collisions are detected too late by this algorithm. This is because of this approach not searching continuously for collisions in the entire trajectory of the vehicle. This property leads to high number of true negatives and a relatively low number of true positives.

The runtime of this algorithm for the issue of notification is always higher than for issuing warnings. This is due to the ghost vehicles for notifications being generated only after no overlap between the ones for warnings is detected.

For the implementation of this approach, special consideration needs to be given to the number of lanes connected to the intersection. When operating at an intersection with multiple lanes for a same direction of travel, a lane-level position accuracy may be needed in order to correctly allocate the ghost vehicle. This means that the algorithm needs to know on which lane the vehicles are located, before predicting their future position.

B.2.4.5 Comparison across Approaches

and Figure B-23 give an overview of the collision-avoidance potential of every approach, as well as their robustness against false warnings across the different scenarios.

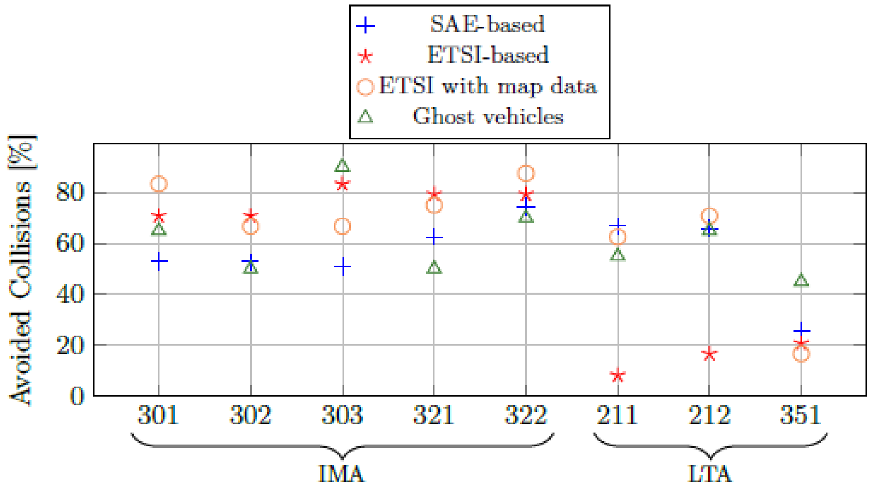

Figure B-22: Percentage of avoided collisions across different approaches.

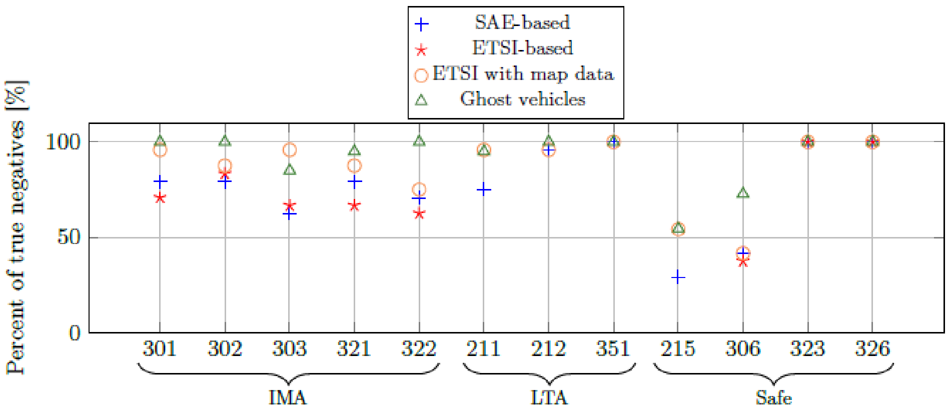

Figure B-23: Rate of true negatives across different approaches.

B.2.4.6 Autonomous Interventions

An autonomous intervention is here defined as a collision-avoidance maneuver performed by the vehicle without requiring a human action. A vehicle can intervene at a later point than a driver, because of the MDRT not having to be considered anymore[32]. This allows for the road situation to become clearer before deciding if an intervention is needed, thus being able to reduce the rate of false warnings. This autonomous intervention is implemented in the form of a 7th driver reaction model having the following properties:

- Reaction time = 0 s
- Brake intensity = 100 %

exhibit the potential of autonomous interventions across the different approaches. This potential is based on the amount of collisions being avoided due to a direct intervention of the system, i.e. the system performs a braking maneuver without any input from the end-user.

[32] Mark Alexander Mages, Top-Down-Funktionsentwicklung einer Einbiege- und Kreuzenassistenten. PhD thesis, Technische Universität Darmstadt, 2008.

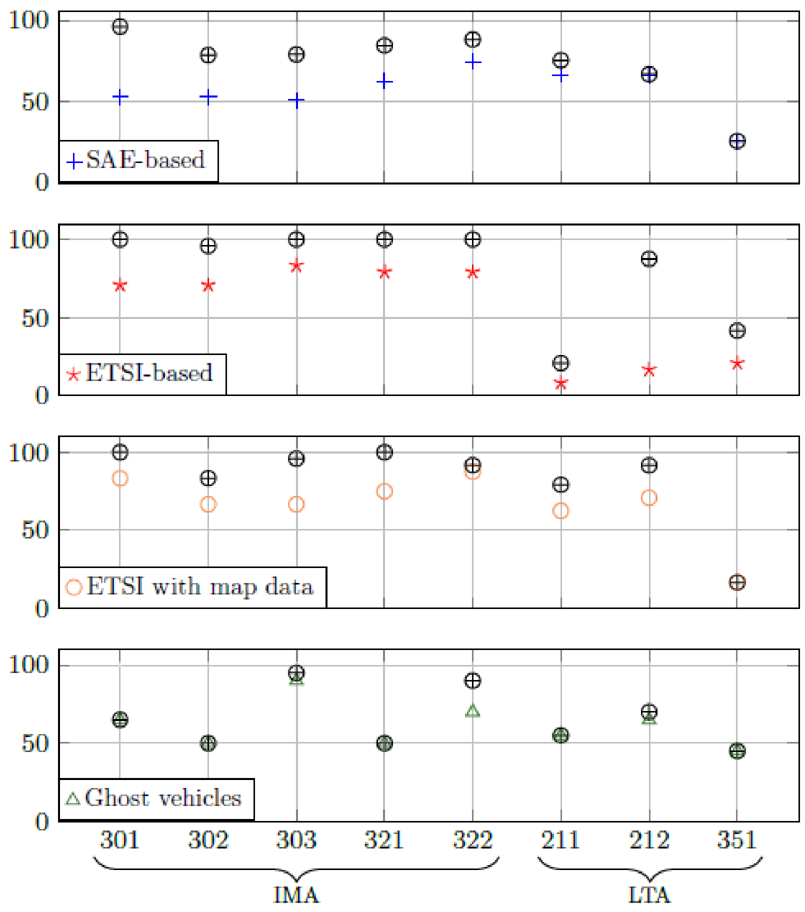

Figure B-24: Potential of autonomous interventions for increasing safety

(The y-axis correspond to the percentage of avoided collisions. The black marks represent the potential increase in safety due to autonomous interventions.)

All four approaches benefit differently from such autonomous interventions. The amount of avoided collisions increases for almost every dangerous scenarios. An important point to take into consideration while developing such systems is the increased potential of false warnings for causing a road accident due to autonomous interventions being more invasive than warnings[33].

In practice, autonomous interventions do not replace warnings and notifications given to the end-user but complement them by preparing the vehicle for taking a collision-avoidance action[34]. They also perform this action when the end-user does not react appropriately to the given warning[35].

[33] Florian Schellin, "Sensitivitätsanalyse eines AS-Systems unter Berücksichtigung von V2XKommunikation zur Vermeidung von Ausgewählten PKW-KRAD-Unfällen," Master's thesis, Technische Universität Berlin, 3 2018.

[34] This preparation includes getting the brakes ready for an emergency brake. This kind of systems can also apply an adequate brake pressure for the current situation, even if the driver does not press the brakes hard enough

[35] European New Car Assessment Programme (Euro NCAP), "Notbremssystem Fahrzeug-Fahrzeug." https://www.euroncap.com/de/fahrzeugsicherheit/die-bedeutung-der-bewertungen/ assistenzsysteme/notbremssystem-fahrzeug-fahrzeug/, 2020.

B.2.5 Driving Test Results

In order to validate the simulation results and to test the portability of the approaches from the simulation into the prototype vehicles, the algorithm corresponding to the ETSI-based approach is applied and evaluated as described in the following subsections. The corresponding software remains active on both prototype vehicles between the different trials.

Test Track

The CARISSMA Test Track is the selected test ground for validating the algorithms using prototype vehicles. Figure B-25 shows an aerial view of the test track accompanied by its dimensions.

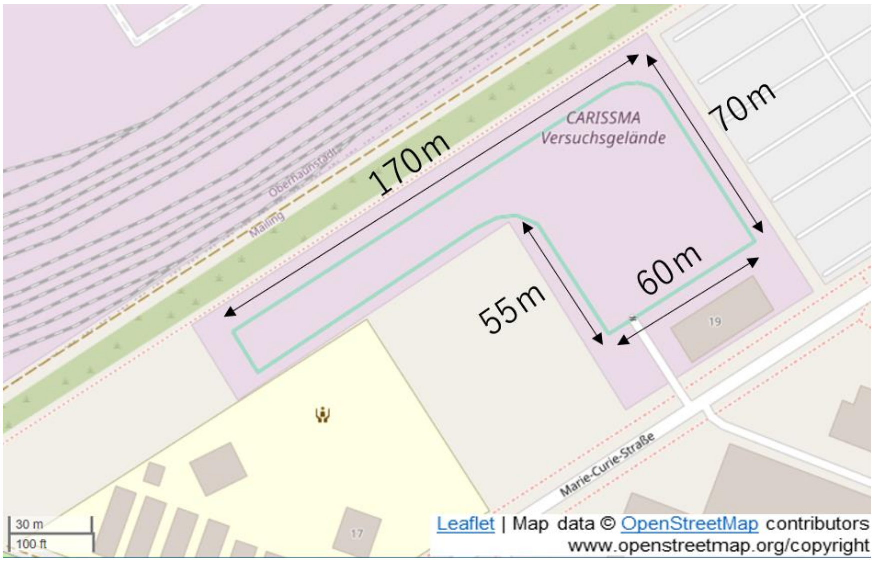

Figure B-25: Aerial view and dimensions of CARISSMA Test Track in Ingolstadt.

Two roads are built inside of the test track using traffic cones. These roads had two lanes in every direction and intersect each other on the northern section of the test track, thus building a T-junction. The eastern part of the test track is used for building non-intersecting roads. Those are used for the Free-ride category as well as an acceleration lane for the vehicles to approach the intersection at an adequate speed.

Scenarios

The following four categories of scenarios from Application Specification (IMA) are evaluated on the test track:

- **Other-vehicle coming from right:** for validating the IMA use cases "Straight crossing path", "Left turn into crossing" and "Other-vehicle turning left from right".
- **Other-vehicle coming from left:** for validating the IMA use cases "Straight crossing path"

and "Left turn into crossing".

- **Oncoming-traffic:** for validating the notifications given for LTA use cases. "*Other vehicle turning left ahead*" and "*Left Turn Assist*" are tested in which a vehicle waits at the intersection before turning left.
- **Free-ride:** for validating the robustness against false warnings. In such scenarios, both vehicles drive freely on the test track without any sort of coordination. This category covers two cases in which both vehicles are driving and in which one vehicle remains static.

Due to the size of the test track, and in order to ensure the safety of the drivers, the speed for this driving test is limited to 40 km/h. Every use case is evaluated using the driving speeds for the Ego-vehicle and the Other-vehicle specified in the following table:

Table B-6: Trial speeds for driving test.

Ego-vehicle	Other-vehicle
40 km/h	40 km/h
40 km/h	20 km/h
20 km/h	40 km/h
20 km/h	20 km/h

(The only exceptions to this arrange are the category Free-ride and the LTA uses cases in which one vehicle remain static.)

Results

Table B-7 presents an overview of the results obtaining during the driving test. For all IMA use cases, two trials are performed with every speed configuration and for both a dangerous and a non-dangerous situation, amounting to a total of 16 trials for each one of the categories "Other-vehicle coming from left" and "Other-vehicle coming from right". For all these trials, both the prototype car and PTW did receive the IMA-warnings while approaching the intersection under dangerous scenarios.

The scenarios corresponding to LTA use cases in which both vehicles approach the intersection are evaluated two times for every speed configuration.

The *Free-ride* trial in which only one vehicle is moving yields a true negatives rate of 100 %, i.e. no false warning is received. For the cases in which both vehicles are moving and the risk of collision is relatively high, a warning is given to both of them and directly followed by a braking maneuver. The vehicles also receive some warnings in non-dangerous situations. In all such situations, the vehicles are driving in opposite directions and following a curve.

Table B-7: Overview of driving test results.

Use Case	Scenario	Trials	TP	TN
IMA	Straight crossing path	16	✓	✓
IMA	Left turn into crossing	16	✓	✓
IMA	Other-vehicle turning left from right	16	✓	✓
LTA	Left turn with oncoming-traffic	8	✓	✓
LTA	Other-vehicle turning left ahead	8	✓	✓
LTA	Waiting before turning left	4	✓	✓
LTA	Waiting before turning left (after half turn)	4	✓	✓
IMA/LTA	Free-ride (Both vehicles moving)	1	✓	✗
IMA/LTA	Free-ride (Only one vehicle moving)	1	–	✓

(The rightmost columns stand for true positives and true negatives. The former refers to the algorithm recognizing a dangerous situation and issuing a warning over the HMI while the latter indicates if false warnings are given.)

B.2.6 Discussion

This chapter describes the scenarios and criteria for the evaluation of the algorithms. All four algorithms are implemented and evaluated inside of the simulation. The ETSI-based approach is also implemented on the prototype vehicles for validation of the simulation results.

For the evaluation inside of the simulation environment, a data set covering relevant accident scenarios is generated, while the different driver reactions to warnings are ordered into six different models, every one having a certain probability of occurrence. Also the different indicators of performance are defined based on the notion of true/false positives and negatives. This concept is expanded in order to differentiate between collisions being detected and avoided, and collisions being detected but not avoided, e.g. due to a too-late detection.

The results obtained through the simulation are then presented. This includes the detection accuracy, the robustness against false warnings and the runtime for the four algorithms. In general, three scenarios are specially challenging for all four algorithms: 351, 215 and 306. The first two correspond to LTA use cases in which the Other-vehicle turns left at an intersection, and the third one pictures the Other-vehicle turning right while approaching the Ego-vehicle from the left. What makes these scenarios specially challenging for the algorithms? The answer lies in the maneuver to be performed by the Other-vehicle being unknown to the algorithm.

The results obtained through the simulation are then validated using the prototype vehicles. For these purposes, the different use cases for IMA and LTA are emulated on a test track. The implemented algorithm is able to correctly distinguish between dangerous and non-dangerous situations for all reproduced use cases. It nevertheless failed to constantly deliver true negatives for the category *Free-ride* while both vehicles are moving. This is specially appreciated as both vehicles drive in opposite directions while approaching a curve, thus confirming the results gathered through the simulation.

All four algorithms are also observed to have a linear time complexity *O(n)* for processing n number of CAMs. And a space complexity corresponding to *O(1)*, because of no information about past messages being stored. The potential of autonomous interventions is evaluated by adding a 7th reaction model. This model represents a collision-avoidance action being performed without having to take the driver reaction time into account.

Abbreviations

ACEM	European Association of Motorcycle Manufacturers
AU	Application Unit
C2C CC	Car to Car communication consortium
CAN	Controller Area Network
C-ITS	Cooperative Intelligent Transport System
CAM	Cooperative Awareness Message
CMC	Connected Motorcycle Consortium
C-V2X	Cellular Vehicle to Everything
DSS	Dynamic Safety Shield
DR	Dead Reckoning
DTI	Distance to Intersection
ECDSA	Elliptic Curve Digital Signature Algorithm
EEBL	Electronic Emergency Brake Light
ENU	East/North/Up
EPSG	European Petroleum Survey Group
ETSI	European Telecommunications Standards Institute
EU	European Union
EV	Ego Vehicle
GNSS	Global Navigation Satellite System
HMI	Human Machine Interface
HV	Host Vehicle
IMA	Intersection Movement Assist
IMU	Inertial Measurement Unit
LIN	Local Interconnect Network
LTA	Left Turn Assist
MAI	Motorcycle Approach Indication
MAT	Maximum Action Time
MAW	Motorcycle Approach Warning
MDRT	Maximum Driver Reaction Time
MLT	Maximum Latency Time
NIST	National Institute of Standards and Technology
OV	Other Vehicle
PER	Packet Error Rate
PoC	Point of Collision
PTW	Powered Two Wheeler
SAE	Society of Automotive Engineers
TTC	Time to Collision
TTI	Tim to Intersection
UDR	Untethered Dead Reckoning
UKF	Unscented Kalman Filter
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
WGS84	World Geodetic System