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Executive Summary of the Thesis

Development and Implementation of Active Pedestrian Safety and Driver Comfort Systems for Connected Vehicles

Laurea Magistrale in Mechanical Engineering - Ingegneria Meccanica

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1. Introduction

Owing to the advancements in the field of communication for vehicular networks and socioeconomic studies, research on modern day mobility is undergoing an unprecedented change in how people will be commuting from one place to another in the future. This change will be the result brought in by the four disruptive trends that we are witnessing at present: *Connectivity, Autonomous Vehicles, Shared Mobility and Electrification*, together known as CASE. They will be shaping the future of cars and the mobility industry itself.

In this thesis work, with inclination towards aforementioned trends, our main goal was the proof of concept of two different driving assistance systems enabled by connectivity, and in particular made possible by 5G network's features: *ultra low latency, high peak data rate, ultra high reliability and high throughput* under high mobility and connection density.

In detail, the work consisted of designing of these systems to experimental test phase of an active pedestrian collision system and a comfortable one for the driver.

The first system, which we have named as the *Pedestrian-Intersection Collision Warning Assistance System (P-ICWAS)* has been designed to enhance road safety at intersections and pedestrian crossings for all road users, focussing on Vulnerable Road Users (VRUs). Its primary objective is to alert drivers of potential collisions with pedestrians who may not be visible to them while crossing the road.

The second system, named as the *Driver Profile Load System (DPLS)* is aimed at improving the comfort and convenience of the driver. By detecting the driver's identity using 5G enabled camera and automatically loading the driver's preferred seat and side-mirror configurations upon boarding the vehicle, based on stored data, it negates the redundant activities to be performed by the driver every-time he boards a car, reducing driver fatigue. The benefits are more profound in case of shared mobility.

The proof of concept of the two designed system was demonstrated at the Base 5G seminar held at Politecnico di Milano. To the best of our knowledge, such an active pedestrian collision prevention system as ours, with V2I communication over 5G network has not been successfully implemented before. At best, we found them in conceptual stages in literature.

2. 5G network for Vehicular Communication

Today, development of Connected Autonomous Vehicles (CAVs) have the possibility to harness support from the latest cellular network, which is referred to as 5G or the fifth generation. Utilizing 5G , which can provide speeds of up to 10 Gbps and a remarkably low latency of 1 ms , the concept of Connected Mobility can take a step forward towards realising the Intelligent Transport System (ITS) of the future. The 5G new radio (5GNR) was introduced in 2015 by the International Telecommunication Union (ITU) as a novel cellular communication standard that has the capability of supporting large-scale, delay-sensitive Vehicular Network applications by employing 5G. 5G offers ultra low latency, high peak data rate, ultra high reliability and high throughput, enabled by Massive Machine Type Communication (mMTC), Proximity Service, Network Slicing and Ultra-Reliable Low Latency Communication (URLLC). Low latency means that data can be transmitted and processed much faster in comparison to the previous generations of wireless technology, ie DSRC and 4G LTE.

Based on the field measurements conducted and analysed by authors in [3], in order to evaluate the performance of three potential vehicular networks, IEEE-802.11p (DSRC), 4G LTE and 5G in Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) scenarios, the results referred to in the *Table 1* illustrate that 5G test network has performed better than the other two technologies in terms of latency (ms), packet loss (%) and throughput (Mbps). This ultra-reliable, low latency network enables vehicles to communicate with other vehicles (V2V), pedestrians (V2P), and infrastructure (V2P) in real-time, allowing for faster response times and better decision making.

Specific to the topic of our thesis, 5G network has the potential to significantly improve vehicle-pedestrian collision avoidance.

Technology	Latency (s)	Packet loss (%)	Throughput (Mbps)
IEEE-802-11p	0.05	17.02	1.48
LTE	0.04	7.5	2.02
5G	0.01	4.07	3.12

Table 1: Performance analysis of DSRC (IEEÉ 802.11p), LTE and 5GTN. [3]

Because of the above mentioned advantages, interest in 5G development will continue to progress for V2X applications, and hence has been used to design our active Pedestrian Collision Warning system.

3. Active Pedestrian Safety

Available literature strongly suggests that the leading causes of violent fatalities around the world is road traffic collisions, and pedestrians are amongst the most vulnerable with respect to such incidents. Moreover, vehicle speed and driver distractions have been found as the significant risk factors in these collisions, affecting both the likelihood of a collision and its severity. Distractions on the road occur when the driver attends to a secondary task unrelated to driving. Three causes of distraction were found by Strayer et al., namely *Cognitive* (when attention is diverted from the driving task), *Manual* (when the driver's hands are not on the steering wheel) and *Visual* (when the driver's eyes are not on the road).

To overcome these factors in relation to pedestrian collisions, there exists Advanced Driving Assistance systems like Autonomous Emergency Braking (AEB) and Forward Collision Warning Systems (FCWS). AEB can automatically detect a potential collision and activate the vehicle braking system to decelerate the vehicle with the purpose of avoiding or mitigating a collision. In comparison to AEB, FCWS only warns the driver and does not automatically apply the brakes to the vehicle. Studying brake reactions of distracted drivers to pedestrian Forward Collision Warning systems, Lubbe et al in their research concluded that the most successful setting for preventing collisions in comparison to any other settings was an audio-visual warning to the driver with an added brake pulse. This setting ensured that all the drivers reacted to the collision warning. In The collision avoidance was most successful when brake pulse warning was deployed as it had the quickest reaction times and the slowest driving speeds upon break application.

Consequently, it was taken into account while designing our driver assistance system, that it would initially warn the driver, followed by taking over and braking autonomously, if the driver fails to react to the warning in order to prevent collision. It was also found in literature that that without connectivity, even fully autonomous vehicles (AVs) are unable to ensure safety, challenges being *Occlusions, Traffic Violation and Behavior Prediction Uncertainty of Pedestrians.* To this end, a 5G enabled V2X communication of data became all the more essential to higher driving automation.

Taking all these considerations into account, our motivation was to design a 5G based Vehicle-to-Infrastructure (V2I) collision warning system (CWS) and conduct experimental tests to improve driver performance/comfort and enhance safety at pedestrian crossings, irrespective of it being a signalised or unsignalised crossing.

3.1. Pedestrian Collision Calculation

A detailed road map is essential for an optimised performance of certain ADASs and navigation of CAVs. In our specific implementation, a local curvilinear road map is generated from Cartesian global reference for the development of the algorithm. Different models can be employed for the task. Cartesian coordinates (X-Y) of the map are fitted using third order polynomials that locally approximate the road centerline angle θ_c as a function of the curvilinear abscissa s. Curvilinear pose is defined as curvilinear abscissa, s, a signed lateral distance, y, and a relative orientation with respect to a reference path describing the center of the lane, ξ as shown in *fig. 1*

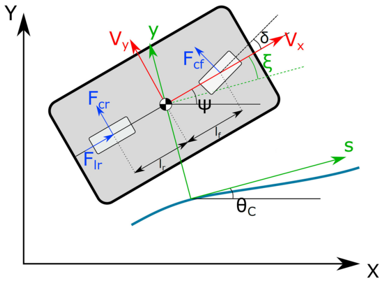

Figure 1: Representation in S-Y coordinate system.

Source: NMPC trajectory planner for urban autonomous driving[2]

The single track dynamic model has two translational degrees of freedom, X & Y, and one rotational DOF about the Z axis. The longitudinal and translational velocities (V_x, V_y) can be represented in s-y coordinate system using the the *eq.* (1) [2]

$$\begin{aligned}\dot{s} &= \frac{V_x cos(\xi) - V_y sin(\xi)}{(1-\theta'_{cs}\cdot y)}\\ \dot{y} &= V_x sin(\xi) + V_y cos(\xi)\\ \dot{\xi} &= \omega - \theta'_{cs}\cdot \dot{s}\end{aligned} \tag{1}$$

Here ξ , heading angle error, is calculated as the difference between the heading angle (ψ) and the angle made by tangent to the path. θ'_{cs} is the curvature of the path at the s coordinate of the point of tangent.

Conversion to the curvilinear coordinate system allows us to use equations of linear motions in the longitudinal direction of motion, for calculating the future position of both the pedestrian and the vehicle as depicted in *eq.*(2).

$$s(t) = u\cdot t + \frac{1}{2}a\cdot t^2 \tag{2}$$

Collision risk of a pedestrian is calculated using the following steps:

1. Calculate the distance between the Vehicle and the pedestrian along the path.
2. Calculate the time to reach the pedestrian.
3. Calculate the position of the pedestrian at the arrival of vehicle.
4. Check if the pedestrian is in the obstruction boundary of the vehicle.

The time that a vehicle takes to reach, Time-To-Reach (TTR), can be calculated using the relative distance along the path, Δs, the relative velocity in s-coordinate and the relative acceleration in s-coordinate.

$$\Delta s = s_{ped} - s_v \tag{3}$$

$$TTR = \begin{cases} -\frac{\Delta S}{v_{r,s}} & \forall v_{r,s} < 0, a_{r,s} = 0\\ -\frac{v_{r,s}-\sqrt{v_{r,s}^2-2\Delta s\cdot a_{r,s}}}{a_{r,s}} & \forall v_{r,s} < 0, a_{r,s} \neq 0\\ -\frac{v_{r,s}+\sqrt{v_{r,s}^2-2\Delta s\cdot a_{r,s}}}{a_{r,s}} & \forall v_{r,s} \geq 0, a_{r,s} \neq 0\end{cases} \tag{4}$$

Here, s_{ped} and s_v are the s-coordinate position of pedestrian and vehicle respectively. $v_{r,s}$ and $a_{r,s}$ are the velocity and acceleration of the vehicle w.r.t. the pedestrian respectively. TTR can not be calculated for $v_{r,s}$ & $a_{r,s} \geq 0$ as the relative distance between the pedestrian and the vehicle does not decrease and for $v_{r,s}^2 - 2\Delta s \cdot a_{r,s} < 0$.

It is to be noted that the s_v in *eq.* (3) is the s-coordinate of the front end of the vehicle. The calculated TTR is used for predicting the pedestrian position along the y-coordinate. It has been assumed that the pedestrian walks at a constant speed.

$$y_{ped}(TTR) = y_{ped}(t) + v_{y,ped} \cdot TTR \qquad (5)$$

Here, y_{ped} is the y position of the pedestrian and $v_{y,ped}$ is the velocity of the pedestrian in y direction. We assume a critical zone in the y direction along the crosswalk. The critical zone consist of the points $(y_v(TTR) + \frac{w}{2} + w_{sz}, y_v + \frac{w}{2}) + y_{sz})$, where y_v is the position of vehicle along the y coordinate, w is the width of the vehicle and w_{sz} is the width of the safety zone around the vehicle. $y_v(TTR)$ can be calculated from velocity and acceleration of the vehicle using *eq.* (2). In our case we assume that these quantities are negligible. TTR becomes TTC if the predicted y coordinate of the pedestrian, $y_{ped}(TTR)$ lies within the critical zone, i.e. in TTR amount of time the vehicle will reach the pedestrian and collision will occur. The safety zone can compensate for the real world inaccuracies of the system. Also, it may prevent startling of the VRUs if the vehicle passes by very close to them.

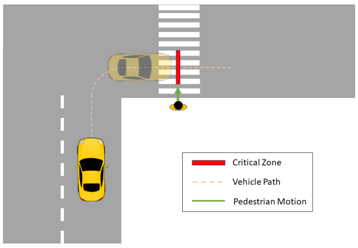

Figure 2: Critical Zone of the potential Vehicle-VRU interaction

If multiple pedestrians are present, above calculations are done for all the pedestrians and the TTC is set equal to TTR of the pedestrian with earliest chance of collision.

$$\mathrm{TTC} = \min\{\mathrm{TTR}_{P1}, TTR_{P2}, TTR_{P3}, ..., TTR_{Pi}, ..., TTR_{Pn}\}$$

where, n is the number of pedestrians.

3.2. P-ICWAS

V2X-based pedestrian collision avoidance system includes pedestrian information acquisition and processing, longitudinal speed planning, longitudinal speed control and vehicle implementation. The pedestrian information is used as the input of the system. The Algorithm comprises of a Map data block, State Estimator Block, Coordinate Conversion block, Pedestrian Collision Detection block, Collision Warning and Bake Decision block and a Brake Actuation block as seen in Fig.3

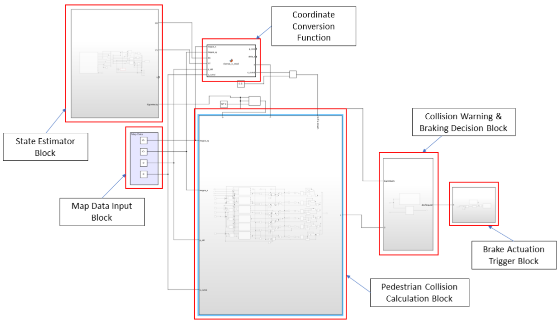

Figure 3: P-ICWAS Algorithm Simulink

Map Data block provides the information of the curvilinear reference of the path to be taken. The state estimator block uses an unscented Kalman filters(UKF) based on single track kinematic model to estimate the velocities, heading angle and positioning of the vehicle in real-time. The estimator uses measurements from the following sensors for estimation:

- One GPS receivers located along the longitudinal axis of the vehicle;
- An automotive IMU placed in the estimated centre of gravity (cog);
- Two tone wheels installed within the disk brakes on the rear shaft;
- An incremental optical encoder connected to the DC motor of the Electronic Power Steering (EPS) system of the vehicle.

The communication system and update frequencies are shown in the Table 2

SENSOR	COMMUNICATION	FREQUENCY
GPS	ETH	10 Hz
IMU	CAN Bus	100 Hz
EPS	Serial Communication by Hard Real-Time System	20 Hz
Tone Wheels	Serial Communication by Hard Real-Time System	20 Hz

Table 2: Sensor Frequencies

Oversampling of the position is handled by switching between two similar filters triggered by the input of serial data. The first one accounts for GPS measurements and the second one provides the position by integration based on kinematic relationships. The estimator can provide an estimate within 25 ms. The Coordinate Conversion Block converts the UTM coordinates UTM coordinates to s-y coordinate system based on the input received from the Map Data Block. Pedestrian Collision Detection block receives the converted state information of the vehicle as well as the pedestrian information from the Infrastructure-side sensor. It then proceeds to calculate TTC as defined in 3.1.

Based on this TTC the Collision Warning and Brake Decision block decided whether a warning should be given, Emergency brakes should be applied or no action is required. It uses two threshold values, TTC_1 and TTC_2 to make the decision. If the TTC falls between TTC_1 and TTC_2, the warn function alerts the user about the possible collision with the pedestrian (Yellow Warning). If the TTC falls below TTC_2, the functions alerts the driver that Autonomous Emergency Braking is active in order to avoid/mitigate the collision damage to pedestrian (Red Warning). The values of TTC_1 and TTC_2 are decided according to the braking process which involves the driver and the braking system of the vehicle. The braking deceleration values are based on the discussion presented in [1]. The AEB deceleration logic is as follows:

- if $v_{car} \leq 30$ km/h , $acc_{req} = -10m/s^2$,
- if 30 km/h $v_{car} \leq$ 50km/h, $acc_{req} = -3.5m/s^2$ for 300 ms,
  followed by $acc_{req} = -6m/s^2$
- it $v_{car} \geq$ 50km/h , $acc_{req} = -3.5m/s^2$,

The braking process is shown in Fig. 4. τ_1 is the driver's response time. It consists of $\tau_1^{'}$, the time driver takes to comprehend the warning, and $\tau_1^{"}$, the time taken to respond and brake. $\tau_2^{'}$ is the time taken by brake clearance and time taken by AEB to receive information and actuate. $\tau_2^{"}$ is the taken by the braking system to build up to the desired deceleration value.

Time to warn (TTC_1) should be decided such that the driver has sufficient time to take responsive action but not long that the warning is triggered frequently for low/manageable risk, distracting the driver and instilling distrust in the warning system. Studies show that driver response time τ_1 is below 1 sec for a alert driver for an expected event and around 1.5 - 2 secs for and unexpected or surprise event. Thus we can set the TTC_1 threshold as TTC_2+2 seconds.

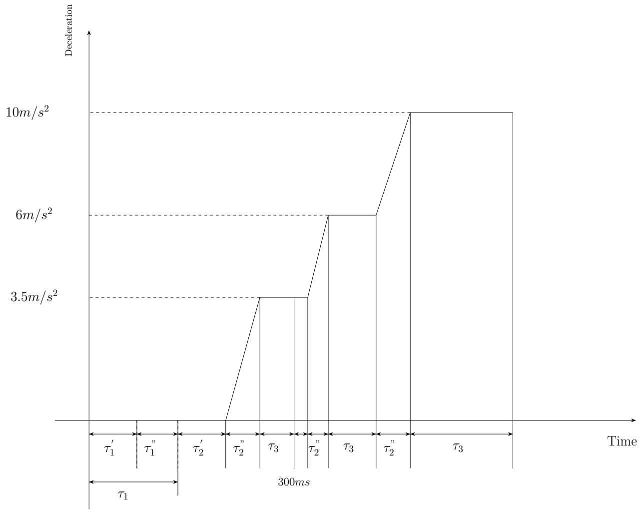

Figure 4: Braking process

In order to set the threshold value of TTC_2, we need to take the braking distance into consideration. Safe braking distance consists of 3 parts,

- Actuator Response Distance
- Braking Distance
- Safety Distance

Actuator Response Distance is the distance traveled by the vehicle in the time interval from when the braking action is initiated and the time when desired deceleration is achieved.

Braking distance is the distance travelled by the vehicle at the desired acceleration request.

Safety distance is a safety measure that adds additional redundancy to the system. It is essential in order to avoid braking too close to the pedestrian and startling them causing panic situation. It also compensates for inaccuracies that may occur in sensing, assumptions and variation in vehicle dynamics due to change in environmental and temporal factors. For a safety distance of 2m, the minimum safety distance, d, is given as,

$$\text{d} = \begin{cases} \frac{v}{3.6}(\tau_2^{'} + \frac{\tau_2^{"}}{2}) + \frac{v^2}{259.2} + 2 \quad for\ v \leq 30kmph \\ \frac{v}{3.6}(\tau_2^{'} + \frac{\tau_2^{"}}{2}) + \frac{v^2-u^2}{90.72} + \frac{u^2-30^2}{155.52} + \frac{30^2}{259.2} + 2... \\ ...for\ 30kmph <\ v \leq 50kmph \\ \frac{v}{3.6}(\tau_2^{'} + \frac{\tau_2^{"}}{2}) + \frac{v^2-46.22^2}{90.72} + \frac{46.22^2-30^2}{155.52} + \frac{30^2}{259.2} + 2... \\ ...for\ v \geq 50kmph \end{cases}$$

(6)

where, $u = v - 3.78$ (kmph). The value of minimum safety distance is then substituted for Δs in *eq.*(4) to obtain the values of TTC_2. TTC_2 indicates that for a TTR value less than TTC_2's value, the vehicle will reach sooner to the the desired position before it can come to a complete stop. In the algorithm a fixed value of TTC_2 equal of 2s to reduce the complexity for initial validation. If the TTC falls below this value the Brake Actuation block sends a signal to the actuate the brakes. The communication between the infrastructure, algorithm and the brake actuator is done on a ROS network.

4. Driver Comfort

Personalized internal vehicle setup and memory features are common in private vehicles. These system improve comfort and convenience. Although not currently unavailable in present carsharing fleets, such kind of systems can improve adoption and continuation of carsharing services. The second system that we have designed and implemented tends to bring similar comfort to carsharing users as well as user of private vehicles.

4.1. Driver Profile Load System

Seat and side-mirror memory systems are being offered by Original Equipment Manufacturers like Volvo, MG, Mazda etc. since early 2010s. However these OEMs have limited their system to two to three profiles. These profiles can be saved by pressing Memory button, usually labelled as 'M' or 'SET', along with the profile button, usually labeled as ['1','2','3'] or ['A','B','C']. These systems, due to limited local data storage and inability identify driver, have limited functionality.

The Driver Profile Load System (DPLS), Fig.6 that we have developed integrates cellular communication technology and driver identification. It primarily utilizes facial recognition program. DPLS comprises of a camera which is used for facial recognition, a 5G cellular user equipment which sends and receives the information regarding driver from the cloud, a joystick for manual input, a control algorithm and seat and mirror actuators.

Figure 5: DPLS System Control Module

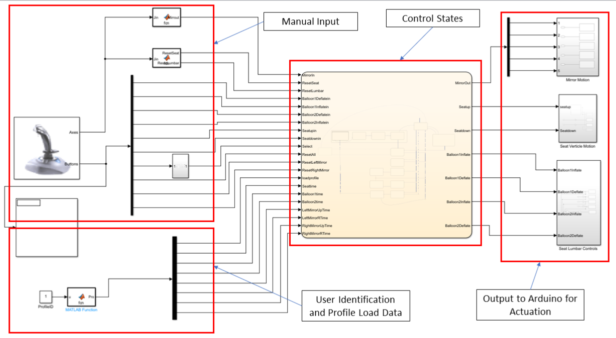

Figure 6: DPLS Algorithm

The functionalities of seat and mirror are replicated by understanding the internal circuitry and duplicating the circuit using an Arduino MEGA 2560 and a 12V Relay board. The simulink algorithm that we developed can read the inputs coming from a joystick, as well as load the previously saved driver profile. Since no position memory sensors are present, saving and loading process is done with the help of system specific calibrated time. Thus, after a proper calibration, time of actuation can be used as a way to measure distance. For every motion of a single degree of freedom, the time to reach from one extreme position to another extreme position is observed and is entered into the developed algorithm.

The Stateflow Control algorithm, Fig. 6, receives 21 inputs and provides 7 outputs to the Arduino. The input which is being read actively depends on the current state of the system. The output is either a high or a low level value, designated to Arduino pins. The output then triggers the relay circuit, thereby connecting the desired circuit and actuating the desired function. The default state of the system is Idle state, i.e. the system always returns back to its idle state from the profile loading state. The system can go to manual state if and only if the manual button is pressed on the joystick. The manual state allows the user to move the seat and the mirror as they desire. The reset state is triggered if a new profile is being set, or by the user when they press the reset button. The reset position is down-left for the mirrors, lowest height and bellows in completely deflated state for the Seat. The reset will loop back to Idle or Manual state, depending on the state from which it was triggered . The profile load State will set the seat and mirrors according to the input profile variables, if the profile is not already loaded.

The profile loading and resetting of position happens in a semi-sequential manner. The left mirror horizontal movement, Seat height and seat bellows are actuated parallely and then left mirror vertical movement, right mirror horizontal movement and vertical movement are actuated one by one. This order is reversed while resetting the positions. When the user tries to initially save his profile configurations for the first time, in "save mode" the input of the user is recorded using the Duration function of Stateflow. Movements away from the origin point is considered positive and movements towards the origin are considered negative. After selecting the preferred position the sum of all the positive and negative movements is stored as the profile value for that function.

The convention for the memory variable is such that the default reset position is the origin and the upward and rightward movement of the mirrors, upward movement of the seat and the inflation action corresponds to positive value. The user can manually set the most preferable position and the variables will be stored in profile data array with a new profile ID. The following shows the structure of profile data array:

$Profile = [Pid, Seat\ time, Lumbar\ balloon\ 1 \ldots$
$\ldots inflation\ time, Lumbar\ balloon\ 2\ inflation \ldots$
$\ldots time, Left\ mirror\ horizontal\ time, Left \ldots$
$\ldots\ mirror\ vertical\ time, Right\ mirror\ \ldots$
$\ldots horizontal\ time, Right\ mirror\ vertical\ time]$

If the user wants to continue as "Guest", the configuration will be set as "Default", i.e. reset position. If the Driver is identified, the script will check if the profile is already loaded or not. If yes, then the system stays in idle state, or else the system will reset the position and then actuate the functions according to values (time in seconds) in profile data array.

5. Experimental Validation and Demonstration

Experimental tests were performed to test the functioning of the P-ICWAS and identify its limitations, if any. Functionality of both P-ICWAS and DPLS were tested using a test vehicle. Finally, both the systems were demonstrated in a recreated real life scenario at Project Base 5G seminar held at Politecnico di Milano, Durando campus

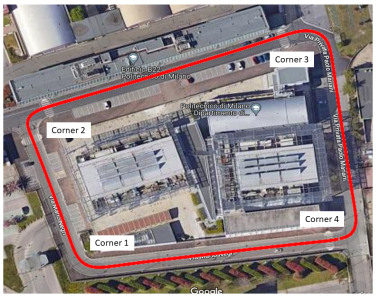

Figure 7: Test Map and Path

The path around the Mechanical department (B23) of Politecnico di Milano was used for testing as depicted in *Fig. 7*. A base station at the department was used for for RTK correction of GPS coordinates. Corner 1 was selected for testing the P-ICWAS function. The test vehicle would go around the path in a clockwise direction. A virtual pedestrian was placed along the path of the vehicle at the end of the curve after corner 1. The aim of the test was to verify if the HMI warning provided to the driver was in time, and to check the AEB trigger functionality of the system. The AEB should get triggered at a sufficient distance from the pedestrian in order to come to a complete halt following a deceleration profile as shown in *Fig.4*.

5.1. Results

The warning and alert were successfully triggered during the test according to the thresholds mentioned in the algorithm, as validated by *Figures 8,9,10*. Warning Time, AEB Alert Time, Velocity, and s-coordinate of the vehicle at the time of trigger were noted and the braking distance according to the deceleration profile shown

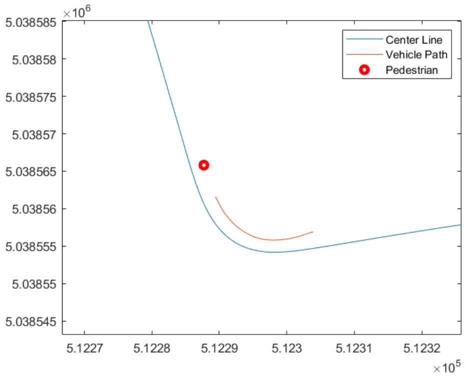

Figure 8: Path taken by the vehicle and the position of the pedestrian.

in *Fig.4* was calculated using *eq.* (3.2). Distance remaining between the pedestrian and the vehicle was calculated as the difference between the final braking s-coordinate and the s-coordinate of the pedestrian. The safety distance achieved was more than twice the safety distance used to calculate braking distance and TTC_2 threshold.

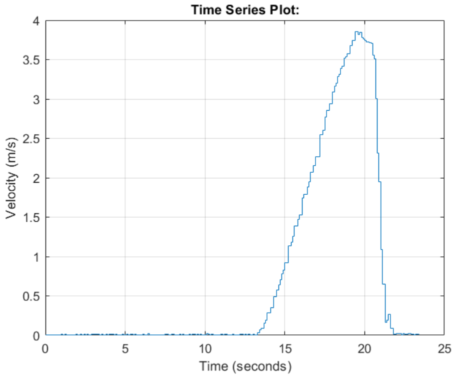

Figure 9: Velocity profile of the vehicle

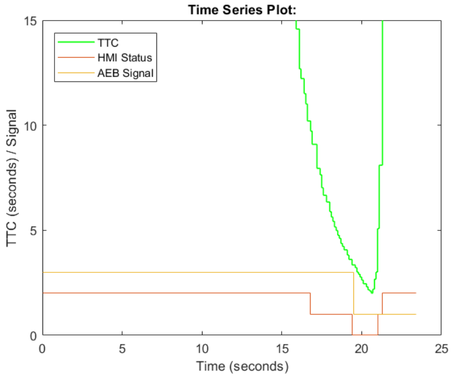

Figure 10: Time history of TTC collision, HMI Warning Signal and AEB Trigger

5.2. Demonstration

The demonstration was done in collaboration with IoT lab of Politecnico di Milano and other PhD colleagues of our research group. For P-ICWAS a camera system which could track upto 6 moving pedestrians at a time and relay their motion information over the Vodafone 5G network. The same test vehicle was also used for this demonstration purpose. Upon receiving the data of the moving pedestrians over the 5G-V2I network, our algorithm was able to calculate the collision possibility, asses the risk and transmit information to the driver using HMI. If the driver could not respond in time, and in case of a risk of collision, signal to trigger AEB was sent by the developed algorithm and AEB was actuated via communication through a CAN network.

Figure 11: P-ICWAS Demonstration

To demonstrate the Driver Profile Load System (DPLS) that we had designed, a 5G enabled camera setup similar to that of P-ICWAS was used, which was designed to use facial pattern recognition algorithm to identify the user The identification was perfectly carried out on cloud and unique user id was communicated to DPLS via the designed DPLS control module. The system then loaded the user profile according to the pre-saved profile data. Then the users switched and the system was able to recognize and load the new driver profile in less than 30 seconds.

6. Conclusions

The two intended Advanced Driver Assistance Systems for pedestrian safety and driver comfort for connected vehicle were developed and implemented. In doing so, we could successfully harness the technological advancements in the field of 5G network, sensing environment and V2X vehicular communications that we had set out to accomplish in the beginning. The algorithms developed for both the designed systems, P-ICWAS and DPLS were successfully validated by the experimental tests conducted and also at the Proof-of-Work demonstration held at the Base5G seminar, organised by Politecnico di Milano.

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Rudrarth Vatsa
Chirag Kothari

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