Using V2X Communications for Smart ODD Management of Highly Automated Vehicles

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***Abstract*— Hazardous events like stationary vehicles on the carriageway, being in most cases unforeseeable and not always easy to detect, pose serious challenges to automated vehicles (AVs). When such events occur, AVs have to determine within limited time and space if permanence in their Operational Design Domain (ODD) will be guaranteed or not, and how to react to ensure passengers' safety and comfort. To cope with such events more effectively and efficiently, in this paper we present a software architecture and logic for Connected AVs (CAVs) that takes into account hazard notification and road signage information from available standard V2X messages to manage ODD-related decisions and reactions in an anticipated way. Differently from earlier works, focusing more on automated compliance to traffic management suggestions by the connected road infrastructure, the presented solution emphasises the active role of the CAV logic in taking suitable decisions based on individual and local situations. We introduce a manoeuvre planner implementing distinct state machines to react to different types of received V2X information. In the resulting procedures, where the driver can be also involved, step goals for a motion planner and path controller are generated. By means of simulations, we demonstrate the benefits of the presented CAV solution against a baseline AV model only relying on on-board sensors. To prove its real-world feasibility, we also report the results of integrating the proposed logic into a CAV prototype and running real-world test-track experiments.**

I. INTRODUCTION

With the goal of making driving safer, more affordable, inclusive and enjoyable, Automated Driving (AD) has the potential to transform mobility and societal behaviour, besides creating important revenues for the involved stakeholders [1]. Being able to operate safely under a complete set of specific conditions called Operational Design Domain (ODD) is an essential pre-requisite for introduction of Automated Vehicles (AVs), especially those with SAE Level 3, where the driver is conditionally released from the driving and monitoring tasks [2], as well as for higher levels. Unfortunately, real-world application scenarios prevent AVs to always operate under their ODD conditions: a number of challenges often requires the driver to take over from automated driving mode. This may compromise safety and user acceptance, with negative implications for AVs marketability. Future technology enablers like V2X (Vehicle-to-Everything) can help bridging ODD gaps and improve AV performance within and outside the ODD. The technical and societal impact of these enablers on AD is currently under analysis in the EU funded Hi-Drive project [3]. V2X is a communication technology by which Connected AVs (CAVs) interact in real-time with other vehicles, as well as with road and digital infrastructure, increasing in time and space situational awareness beyond AV sensors' range and providing explicit information beyond sensors' interpretation of the reality. As an example, CAVs can receive notifications about road hazards downstream when not yet visible to on-board sensors. An anticipated and detailed description of the hazard (e.g. a roadworks blocking two of four available driving lanes at a precise point of the highway) can help AVs deciding whether to keep driving automated (hence bridging a possible ODD gap), or to ask the driver to take over. Should a Takeover Request (ToR) be unavoidable, the earlier V2X notification would allow the driver to intervene much before reaching the hazardous location and with a better situational awareness. Finally, Minimum Risk Manoeuvres (MRMs), if needed, would be more comfortable and take place at more convenient locations thanks to the time advance gained via V2X.

In this context, this paper describes an Automated Driving software architecture that includes modules for early consideration of received V2X information to manage tactical planning decisions regarding permanence within- or exit from the ODD more effectively. Assessment of the added value of this CAV solution compared to a baseline AV only based on on-board sensor is presented via simulation results. First experiences from integrating this architecture in a real CAV prototype are also reported.

II. RELATED WORK

Usage of V2X to extend the capabilities of current AVs has been already envisioned by various industrial organisations driven by car manufacturers [4], telecommunication players [5] and others [6]. CAV proof of concepts have been also presented in a number of research and innovation projects. The EU H2020 MAVEN project has demonstrated usage of V2X messages from the road infrastructure [7] to facilitate AD through intersections [8]. The German IMAGinE project has proposed V2X protocols to realise cooperative automated manoeuvring use cases like merging or overtaking, among others [9]. Similar AD software architectures for management of V2X messages were presented in [10]. Nevertheless, these architectures are used to compare on-board sensors to V2X in terms object detection capabilities, not in terms of event management like proposed here. More recently, the

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EU H2020 TransAID project has presented use cases and novel V2X messages for mitigating the negative effects of ToC (Transition of Control) and MRM at transition areas (where the ODD of multiple vehicles is expected not to be supported). In this context, the road infrastructure sends individual V2X messages to multiple CAVs, explicitly suggesting executing ToCs at convenient separate locations to prevent that all takeovers take place at dangerous areas (e.g. roadworks) [11]. As such, TransAID CAVs manage their ODD by mainly following advices from external entities as a result of sophisticated traffic management strategies and without applying local algorithms. Compared to TransAID, the solution proposed in this work uses standard V2X services already deployed and operated, in a harmonized way under the C-Roads platform, by various European highway operators [12]. The C-Roads services use RSUs (Roadside Units) to broadcast DENM (Decentralised Environmental Notification) and IVIM (In-Vehicle Information) V2X messages. By processing this information, and crossing it with its current status and capabilities, a CAV using the proposed solution operates a smart management of ODD decisions: if the content of those messages guarantees the vehicle to stay within its ODD boundaries by applying specific countermeasures (e.g. slowdown, lane changes, etc.), then AD will be kept. On the contrary, if no safe assumption can be made, the CAV will initiate earlier reactions aimed to request the driver to take back control.

III. Concept

When an AV faces an hazardous event, there is limited time to assess if permanence in its ODD will be compromised. If this is the case and the AV is about to cross its ODD boundaries, it has to manage the situation as fast as possible to determine the safest reaction. In some cases, asking the driver to take back control might be unsafe, and directly recurring to a MRM like an emergency brake would be necessary. The here proposed AD software architecture can manage occurrence of sudden hazards and has the ability to elaborate optimised strategical reactions if such events are known upfront by V2X notifications and signage (CAV solution). Leveraging on this early knowledge can prevent situations where it would be too late to act safely or comfortably, hence managing ODD in a smarter way.

A. V2X - DENMs and IVIMs

In a way, V2X can be seen as an improved and smart sensor by which a vehicle increases its environmental perception and achieves more precise information. Installing RSUs at favourable positions like on poles or highway gantries allows communication ranges of several hundreds of meters. Information included in V2X messages is standardized. In Europe, DENMs notify occurrence of a road hazard and detail its type, position, relevance traffic direction and, optionally, the lanes that are affected [14]. IVIMs inform about currently applicable variable message signs (e.g. speed limits, lane closures, etc.) and specify sign type, relevance zone (i.e. road section where the sign applies; applicable lanes in case distinct signs apply to distinct lanes), and the type of vehicle the signs refer to [15]. In recent years, European C-Roads highway operators have collaborated with the car industry for determining an optimal RSUs placement (i.e. upstream) as well as DENMs and IVIMs content setting. This guarantees vehicles to consider events downstream relevant early enough. When receiving a DENM or an IVIM, the vehicle analyses its content to determine if it is relevant or not (e.g. if the relevance traffic direction in the message matches the current driving direction, etc.). If relevant, the message content is passed to the AD software to assess its impact on ODD-related decisions as explained in the following.

B. Software Architecture

The AD software architecture implemented and used in this work is an extended version of the ROS2 architecture proposed by Reke et al. [16]. A simplified diagram of the proposed software architecture is depicted in Figure 1. It is composed by a vehicle-specific part and a vehicle-unspecific part. The vehicle-specific part shall contain interfaces and drivers for actuators and sensors installed on a given vehicle, while the unspecific part contains software modules that can apply to a variety of different vehicles seamlessly. When the AD software is started up by setting a destination, the route planning module calculates the fastest route to reach it. A set of candidate lanes along the computed route are passed to the motion planning module. At the same time, constraints like speed limits, special lanes etc. are passed to the manoeuvre planner. Based on the current constraints and possibly available V2X information, the manoeuvre planner determines which lanes should be driven out of the candidate ones, and which speed limit should be followed. The decision is passed to the motion planning module as a step goal. The motion planning module takes into account the environmental model, in terms of detected objects, and performs simple operations like changing lanes or adapting to a speed to achieve step goals. Set values for path and speed are calculated by the motion planning module, which results in lateral (steering) and longitudinal (velocity) controls of the vehicle. On the vehicle-specific side, the vehicle interface module transmits set values to the steering, brake and throttle actuators. The rest of this section describes in a detailed way the logic implemented by each of the mentioned modules.

1) Route Planner: The route planning module uses a special type of Open Street Map [17] format called Lanelet2 [18]. A Lanelet2 map is made of multiple atomic segments of a lane called *Lanelets*. Each Lanelet has attributes like *driving lane* or *emergency lane* and can have regulatory elements like speed limits or other traffic constraints. Based on the loaded map, the fastest route is planned. A route is not a single path, it can rather contain multiple parallel paths on one road (candidate lanes). Candidate lanes are passed to the motion planning module; constraints like speed limits or presence of lanes of restricted use (e.g. emergency lanes) are passed to the manoeuvre planner module.

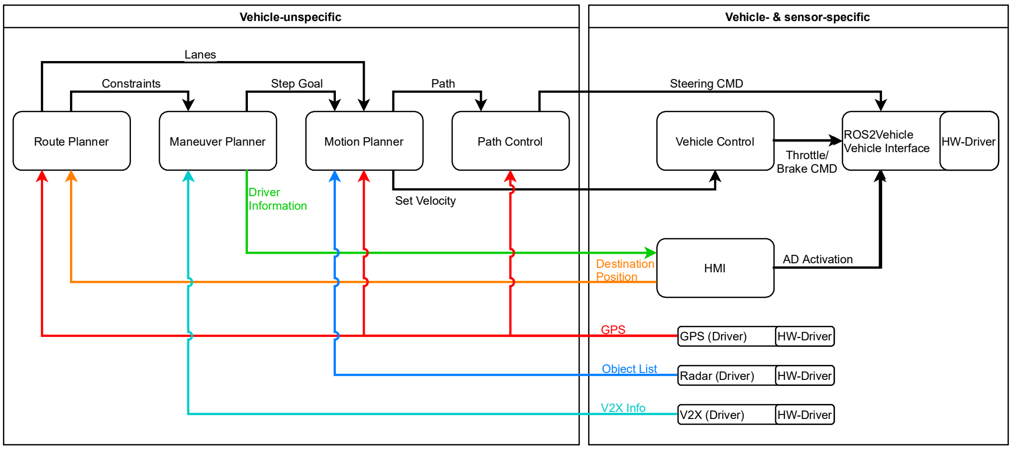

Fig. 1. AD SW Architecture [13]

2) Manoeuvre Planner: The Manoeuvre Planner module shall generate a step goal for the Motion Planner module. To do so, it implements distinct state machines to handle different types of events. A state machine can be described as a sequence of states, each of which can influence the step goal. A step goal contains the following variables:

- **speed_limit** (speed limit from manoeuvre planner)
- **distance_to_event** (distance to the event position)
- **event_extension** (distance, after the event position, to the point where the event extends)
- **designated_lane** (lane guidance for the motion planner)
- **driver_alert** (if true a ToR will be triggered on the HMI)

As an example, Figure 2 shows the state machine that is called when the AD software receives a V2X notification about a stationary vehicle event downstream (similar state machines can be implemented for other types of V2X notifications or road signage). In the entry state, the distance to the event decreases as the vehicle approaches the event. At this stage, the logic shall recognise if the lane blocked by the stationary vehicle is known. If this is the case (i.e. the lane is specified in the V2X message), then the lane is considered locally *applicable* when the CAV is currently driving on it. The step goal is set in this case to *change lane* to the next free lane and returns when the event is passed. Else, if the lane is not applicable, the step goal is set to *keep the current lane* until the event is passed. If the lane of the stationary vehicle is unknown upfront, the event is considered applicable on all lanes. In that case the next state checks again the distance left to the event. A transition to the driver alert state occurs when reaching the distance the CAV would drive in 10 seconds at the current speed plus an offset to decelerate. On entry, the driver alert is set to true and on exit it is set back to false. The sequence ends when the driver takes over and the CAV enters manual driving. If the driver does not intervene, the state machine transitions into the MRM sequence. Figure 3 shows a flowchart of the state machine for the MRM. It starts by immediately setting the speed limit in the step goal to a predefined speed (e.g. 20 kph). If an emergency lane is available (based on the information passed from the route planner) the designated lane is set to *change onto the emergency lane*. When reaching the emergency lane, the speed limit is set to zero to stop the CAV. If no emergency lane is available the vehicle enters the stop vehicle state directly on the ego lane. The MRM sequence can only be completed by a driver intervention.

3) Motion Planner: The motion planner module continuously receives an updated step goal. Moreover, it has information about available lanes, CAV current position and

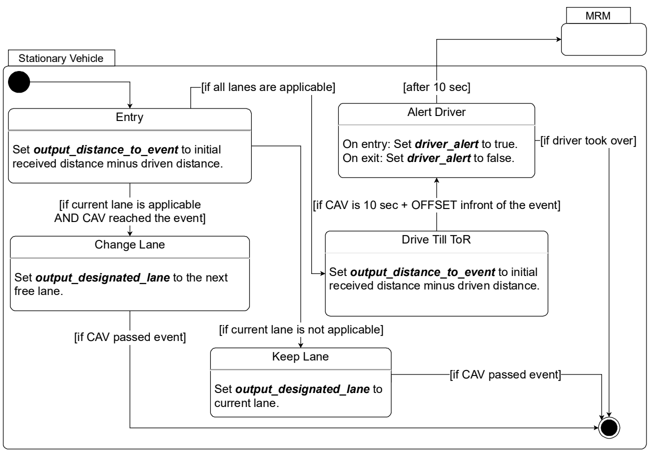

Fig. 2. Flowchart for Stationary Vehicle scenario.

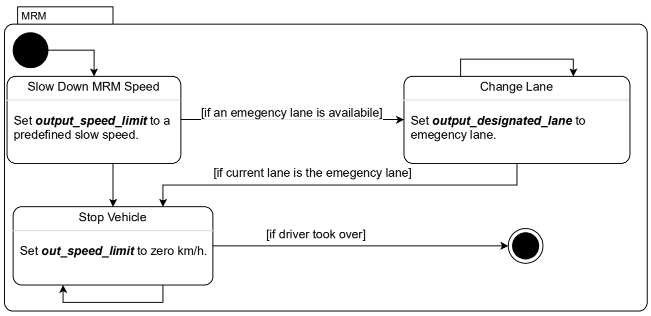

Fig. 3. Flowchart for Minimum Risk Manoeuvre.

surrounding objects. With all this information, the motion planning module shall achieve the step goal within the boundaries given by the environmental model. Objects are filtered to match those that are directly in front or directly behind the CAV as well as those in front or behind on the left and right lane. Based on the filtered objects and the speed limit in the step goal, set speeds are calculated. Similarly, lane changes are managed in a way to be executed only if a safe margin to the filtered objects is identified. If the object in front of the CAV is 30% slower than the CAV, the motion planning module triggers a lane change automatically. When a lane change is executed, a path to the target lane is calculated based on the CAVs speed and forwarded to the path control. The calculated set speed is passed to the vehicle control.

4) Vehicle Controlling: Vehicle controlling is split into two separate modules. The path controlling module handling the lateral control uses a modified version of the controller of Chajan et al. [19]. The longitudinal controller is implemented by two PID controllers, one for brake percentage and one for throttle percentage.

IV. Validation setup

The previously described AD software architecture has been validated via simulations as well as with initial integration in a real CAV prototype, using a reference application scenario as described in the following.

A. Application scenario

We consider an early reaction to road hazards notifications. Figure 5 and 4 show a highway section on which an hazardous situation is occurring. In figure 4 the oncoming red vehicle is a CAV, and therefore is able to receive DENMs from the RSU. By being informed about the hazard, the vehicle can assess the impact on its ODD and act accordingly. By contrast, in figure 5 the red vehicle is an AV, not connected and therefore not able to receive notifications. It has to detect and evaluate the road hazard by use of its on-board sensors. Nevertheless, sensors have hardware limitations, their range may be compromised and in some cases too short to detect the hazardous situation soon enough to react safely. Moreover, the field of view (FoV) of sensors could be affected by obstructions impairing the line of sight: the hazardous situation could be behind a slope or around a corner, limiting the line of sight down to a few meters. Adverse weather conditions could compromise sensor range and performance too. To show how V2X outperforms other sensors in detection capability and could assist in case of compromised sensor performance and range, a stationary vehicle-hazard scenario is considered. The presented CAV solution, as well as the baseline AV approach, only relying on on-board sensors, have either to brake or change lane to evade the stationary vehicle and avoid an accident.

B. Simulation Setup

The above described scenario (see figure 6) is simulated in IPG Carmaker as Software in the Loop Simulation (SiL). The

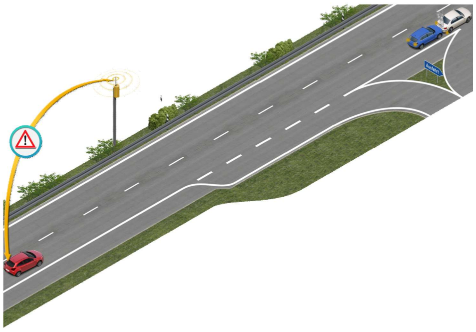

Fig. 4. V2X-based hazard detection (© C2C-CC) [4]

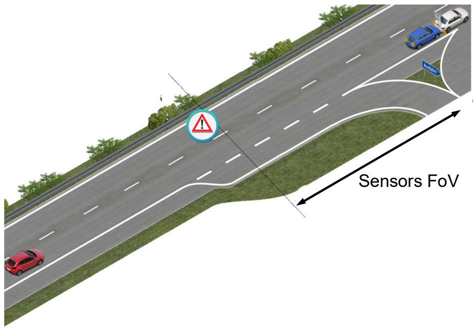

Fig. 5. Hazard detection via on-board sensors (© C2C-CC) [4]

SiL allows creating the scenario virtually and testing the AD software in different configurations. A vehicle implementing the proposed AD software and a vehicle dynamics model very similar to the real vehicle is instantiated and simulated on a multi-lane highway where a stationary vehicle is placed further downstream. The vehicle is configured to have a front-facing radar sensor whose range is set to different values at different simulation runs to emulate distinct situations where the stationary vehicle may be out of sight in the real world. If and when to trigger receptions of V2X notifications at the Manoeuvre Planner during a simulation run can be managed within the AD software itself. This allows emulating realistic V2X reception behaviours and overcomes the absence of V2X models in IPG Carmaker. Two configurations were set up, in the first configuration the stationary vehicle blocks the road completely. In the second one, the stationary vehicle blocks one lane of a three lanes-carriageway plus emergency lane (see Figure 6). In both configurations, the vehicle starts 860 m from the stationary

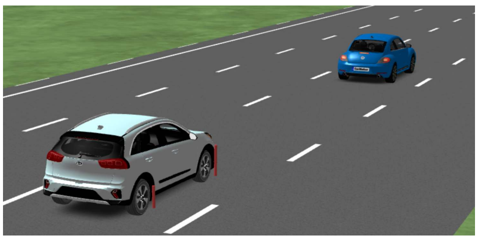

Fig. 6. Application scenario simulated in IPG carmaker

vehicle and accelerates until it reaches its travel speed of 100 kph.

C. *Real-World Setup*

As a proof of concept of the proposed AD software, the architecture has been integrated in the KIA Niro CAV prototype shown in Figure 7. This vehicle was retrofitted with suitable sensors and control units to cover the use cases of the Hi-Drive project, independently from official KIA series developments. A V2X antenna connected to an On-board Unit (OBU) was also integrated to receive and process messages using the ETSI ITS-G5 communication standard. The CAV prototype can be controlled by a drive-by-wire function, which can be overruled when the driver intervenes [16], [13]. With this setup, real AD tests have been performed on a proofing ground section with two driving lanes. A RSU was used to transmit pre-defined V2X messages (see Figure 7). It was configured to transmit DENMs warning of a stationary vehicle downstream on the rightmost driving lane. It is important to highlight that for these first integration tests, where the only objective is to verify the feasibility of the proposed concept, a real stationary vehicle is not physically present at the position indicated in the DENM. Moreover, the DENM is simplistically configured to announce relevance of the hazard only 200 m before the stationary vehicle position. In currently operated C-Roads services, DENMs are profiled to be considered relevant by vehicles at least 600 m before reaching the hazard, along a set of consecutive path points, called "trace", leading to the notified hazard position [20].

Fig. 7. CAV Prototype and RSU used for real-world validation

V. Validation Results

Validation of the presented AD software architecture is reported in this section starting from simulation results and followed by real-world prototyping proof of concept experiences.

A. *Simulation Results*

In simulation, a comparison between the baseline AV approach, only relying on on-board sensors, and the proposed V2X-enhanced CAV solution was established. In this context, simulation offered the benefit to push the sensor detection capabilities to their limits till an accident would possibly occur. As described in section IV-B two configurations were

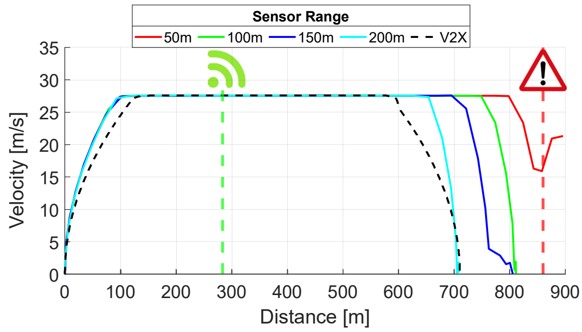

Fig. 8. Simulation when the hazard affects the whole carriage way: impact on velocity profile

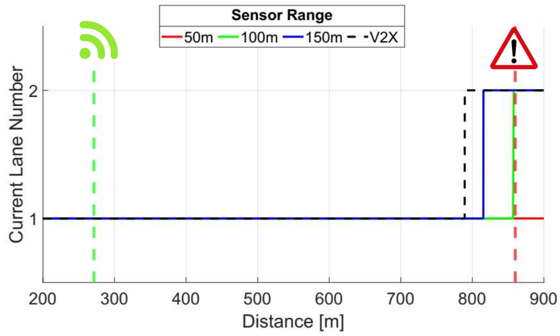

Fig. 9. Simulation when the hazard affects only one lane: impact on lane change behaviour

tested. Figure 8 shows the configuration where the stationary vehicle blocks the road completely and the vehicle has to stop. Starting with 200 m, the sensor range of the baseline AV is decreased by steps of 50 m at subsequent simulation runs. In all these runs, the baseline AV had to perform an emergency braking manoeuvre. With the sensor range set to 50 m, the AV could not stop in time and would have collided with the stationary vehicle. In comparison, the proposed CAV solution receives and consider relevant the DENM notification 600 m upstream, in line with the previously mentioned C-Roads settings. Figure 8 shows that the CAV performed the process described in figure 2, where it tries to alert the driver during 10 seconds before starting a MRM smoothly decelerating and stopping on the emergency lane. Figure 9 shows the configuration where the stationary vehicle blocks only one of multiple lanes. The graph shows on which lane the (C)AV drives at a given distance (keeping a constant speed of 100 kph). The baseline AV approach had to detect the stationary vehicle and perform a lane change. With a sensor range of 100 m the AV made the lane change just in time with only a few meters margin. With a sensor range of 50 m the simulation shows that the AV would have collided with the stationary vehicle. Compared to this, the proposed CAV solution would again react earlier, safely evading the stationary vehicle with an anticipated lane change, without alerting the driver or leaving its ODD.

B. Real-world prototyping

Integration of the presented software architecture on the CAV prototype allowed showing, in a reduced setup, the feasibility of the proposed approach beyond the theoretical verification obtained in the simulated space. Figure 10 shows the CAV's speed and driven lane number as a function of the driven distance. The red marker indicates the point where the stationary vehicle would be according to the hazard position indicated in the DENM. The green marker shows the point where the received DENM notification is considered relevant by the software architecture (200 m before the hazard) and starts to be processed as shown in figure 2. The received DENM notifies about a stationary vehicle on the outermost lane (lane 1). As expected, the CAV reached its constant speed of 90 kph and performed a lane change to the left (lane 2) to evade the stationary vehicle in time and avoid a collision. After that, the CAV continued to drive on lane 2 for the distance indicated by the DENM's hazard extension before it changed back on to the outermost driving lane (lane 1).

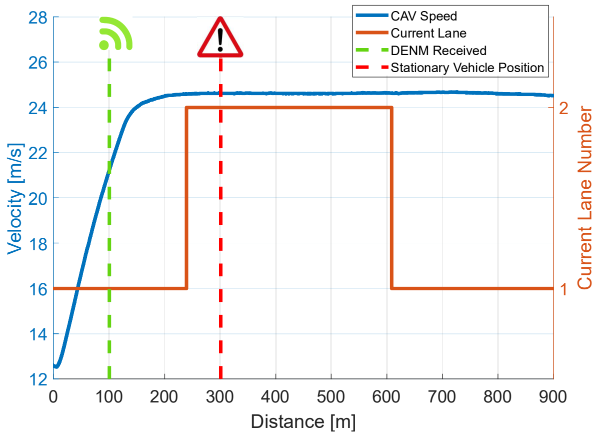

Fig. 10. Prototyping validation when the hazard affects only one lane: impact on lane change behaviour

VI. Conclusion and Outlook

This paper presented an AD software architecture taking advantage of V2X information to perform early decisions on ODD permanence and determine the safest and more comfortable automated reactions. Simulation in different stationary vehicle hazard scenarios showed that the proposed approach guarantees safer MRMs and more timely evasive manoeuvres compared to a baseline AV possibly suffering from sensor limitations. In addition, the proposed logic proved to work equally in real-world experiments via integration and execution in a CAV prototype. Future work will focus on validation in reaction to other types of V2X hazard notifications and road signage in suitable scenarios, especially in more extensive real-world tests where the CAV prototype is compared with respective AV baseline implementations.

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