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EVALUATION OF PLATOONING CONTROL MODEL TOWARDS SAFETY OF INTENDED FUNCTIONALITY WITH BASIS ON OPERATIONAL DESIGN DOMAIN

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Abstract. *This research aims to understand the implications from the concept of ‘Safety of Intended Functionality’ (SOTIF) as stated in ISO/PAS 21448 to the dynamic modeling of vehicle driving assistance systems, by using the example of platooning as dynamic driving task (DDT) for use by heavy trucks that is represented by a control model. From the understanding of SOTIF as the safety of a driving automation feature working within specification and system-wide available capability, the operational design domain (ODD) concept stands out as basis for the assessment of vehicle system behavior as directed by the control model, where driving scenarios make building blocks to the system. This case study starts over with addressing the ODD for the platooning task with 110 km-long Dutra motorway span in regard to the location of motorway exits and refueling points through a Google Maps survey, with processing it in terms of exit angles and curvatures for the purpose of programming appropriate truck deceleration. The platoon is characterized in combinations of up to 6 vehicles according to CONTRAN-regulations, each one carrying a GVW is up to 57 tons with a minimum power-to-weight ratio of 7,5 kW/ton. The control model considers longitudinal control, which is run against scenarios where other vehicles tend to place themselves between vehicles or cut-through with short distance to the front of vehicles in the convoy. The simulations result indicate the need to regulate control triggers in appropriate distance and anticipation from event triggers, and set adequate control procedures for dynamic load distribution across vehicle braking systems.*

Keywords: *vehicle dynamics, driving assistance, platooning, safety, SOTIF*

1. INTRODUCTION

Moving people and goods to meet mobility demands at reasonable speed leaves little room for error. Especially in road traffic, the World Health Organization (WHO, 2018) points out speed and distractions as major factors in traffic incidents with time and asset losses, frequently resulting in human fatalities. The mobility industry develops driving assistance systems to reduce the costs of mobility, with effect to improving efficiency and safety. (Bengler et al., 2014). There is need for awareness to safety as a cautionary approach to ensure driving safety in compliance with the law; engineers of road vehicle systems need to exceed established good practice to ensure traceability and transparency in the vehicle development process, and as a demonstration of good faith to society (Wu, 2016).

Koopman & Wagner (2017) see the safety of driving automation features as comprising their compliance to traffic laws, their ability to evade hazardous driving situations, and their resilience in recovering from failure incidents (Koopman & Wagner, 2017). There is need to establish engineering skills up to the task of implementing proven safety benefits, with clear procedures and metrics.

The purpose of this paper is to undertake a software-based verification of a driving assistance system model with compliance to the ADAS specification ISO/PAS 21448 (ISO, 2019) about safety of the intended functionality regarding the driving automation feature of platooning for heavy-duty transport vehicles. This is performed on a functional model implemented in Matlab/Simulink with ISO/PAS 21448 as basis to verify the intended platooning driving function for heavy duty vehicles as performing safely.

2. BACKGROUND

The advance of electronics as platform for implementing control systems involves the integration of sensory, processing and actuation devices, leading to an increasingly complex vehicle development process. The aim of satisfying functional requirements elicits systems engineering competences in automotive development (Winner, 2013). The awareness to safety implications of driving assistance functions leads the technical community to pay closer attention to the uncertainties involved in driving functions carried out by technical systems, whose failure can lead to traffic hazards that skilled drivers cannot recover from and make harm to assets, infrastructure, and human life (Bergmiller, 2013).

While the firstly available technologies focused the modulation of road vehicle behavior in emergencies – ABS (anti-lock braking system) for braking and ESC (electronic stability control) for steering, for instance – more recent technology developments such as ACC (adaptive cruise control) involve the delegation – by the driver – of acceleration and braking to control systems following the vehicle in front (Tango & Montanari, 2006). These changes increase the relevance of supervisory skills by drivers and thereby the need for understanding the changes in cognitive load on the driver by delegated driving automation features, including the requirement for humans to adapt their perception and skill towards the conditions these systems establish (Saffarian, De Winter & Happee, 2012).

Along with the changes in cognitive workloads to the driver by driving assistance systems, whose reduction in driver engagement runs counter the higher reasoning required by their user interfaces, the availability of sensory technologies and computing power enables the mobility industry to envision the prospect of automating the driving task altogether. One premise to implementing driving automation features for that purpose is the need to ensure predictability and controllability in their performance, which requires a safety-focused approach to prove the intended reduction of risk as result of their implementation (Weitzel, 2013).

A challenge in designing driving automation features, and the driving assistance systems implementing them, is the coupling between vehicle dynamics with focus on the dynamic driving task (*DDT*) with safety approaches aiming at the *safety of intended functionality (SOTIF)* of driving automation features. A review on the background for this paper considers these two fields together so that to provide understanding on the developments performed so far in these two areas, which enable the approach of a driving automation feature as proposed in this paper.

2.1 Safety of intended functionality

The design of driving assistance systems and the implementation of driving automation features requires road vehicle engineers to be aware to both internal and external safety considerations through the vehicle development process. On the one hand, the *functional safety* approach by the ISO 26262 standard (ISO, 2018), addresses the emergence of driving hazards *when components fail to perform within specification* or cease to function entirely while undergoing the *DDT*. Saberi et al. point out that the ISO 26262 reliability viewpoint suffices for systems with clear functionality, yet the uncertainty in vehicle behavior under a diversity of use cases requires the assessment of triggering conditions. A comparison between those viewpoints in a system perspective is shown in Figure 1 (Saberi et al., 2020).

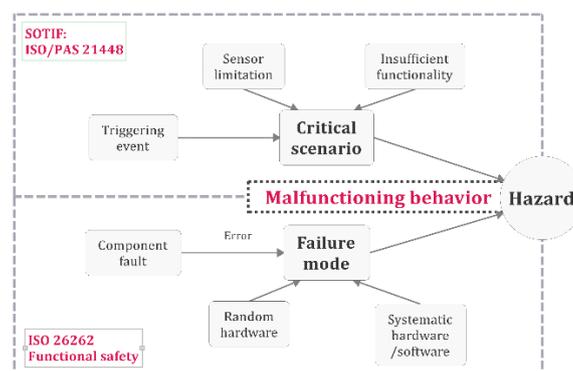


Figure 1. Scope overview between SOTIF and functional safety from a system perspective (Saberi et al., 2020).

Therefore, on the other hand, and in completion to the one, the *safety of intended functionality (SOTIF)* approach by the ISO/PAS 21448 specification (elements shown in Figure 2) addresses hazards that may emerge during the DDT even when there is no fault in any component – the systems *work to specification as intended by design* (ISO, 2019). In association to this, interferences from the environment, or abnormal/sneaky relationships between system elements, can trigger unknown behavior with implications to the safety of driving automation features (Saber et al., 2020). The SOTIF concept conveys the understanding that vehicle systems may fall short of being robust to interferences or disturbances from the environment, or may insufficiently perform the processed function to safety requirements in traffic. The ISO/PAS specification (ISO, 2019) aims to design situational awareness into driving automation features in four parts:

- The intended functionality content regarding the description of driving automation features and the system architecture that is intended to accomplish them.
- The assessment of hazards that may emerge from the intended functionality as performed through the implementation of driving assistance systems.
- The identification of circumstances triggering the emergence of hazards due to insufficiencies in models, algorithms, hardware, and mechatronics. And,
- The setting of risk mitigation measures through functional modifications in the vehicle system to improve the *safety of intended functionality*.

Design level, purpose	Functions, define intended functionality	Systems, implement intended functionality
Inputs	Description, goals and use cases	Description of system and elements
Directives and premises	Expected level of automation/authority over vehicle dynamics	Description and behavior of sensors, controllers, and actuators
		Assumptions on the use of inputs and purpose of outputs
Components and relationships	Dependencies on and interactions with driver and passengers	Concepts and technologies for the system and subsystems
	Dependencies on and interactions with pedestrians and other road users	Limitations, designed countermeasures and supportive architectures
	Dependencies on and interactions with relevant environment conditions	The system degradation concept, and respective warning strategies
	Dependencies on and interactions with the road infrastructure	Dependencies on and interactions with other functions and systems

Figure 2. Content of functional and system specifications from ISO/PAS 21448 (ISO, 2019).

Then, modern tools such as Matlab/Simulink and Modelica use formal modeling languages to augment structural into computational models in Model-Based Systems Engineering environments (D’Ambrosio & Soremekun, 2017). At the same time, Bagschik *et al.* figure the need to expand the safety focus from functional safety, through the concept of behavioral safety, on whether the vehicle can perform intended behaviors in operation (Bagschik et al., 2018). With basis on addressing uncertainties of intended behavior, SOTIF is first defined from functional and system specifications whose recommended content as per the ISO/PAS specification includes elements as shown in Figure 2 (ISO, 2019).

The SOTIF specification characterizes hazards through a scenario modelling approach comprising possibilities of system application (use cases), attitudes and events playing out in the use environment (scenarios) and elements of the use environment along their boundaries (scenes). Elements of the two latter concepts will form situations under which a driving automation system needs to work, appropriately, thus defining a similar element to the SAE J3016 standard *operational design domain (ODD)* (SAE, 2016). Figure 3 shows the perspectives ODD.

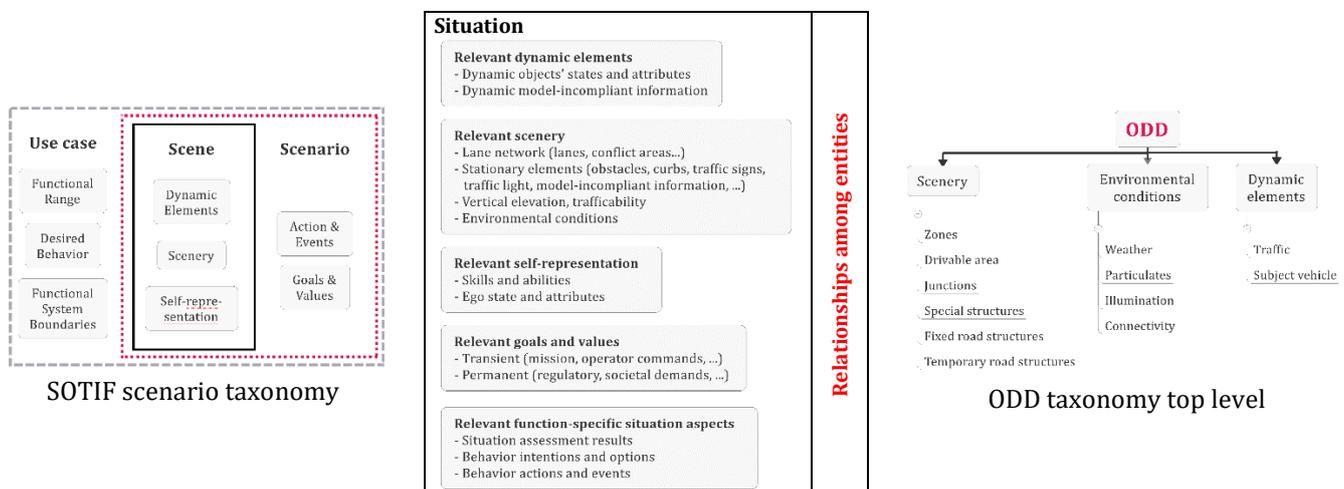


Figure 3. Operational design domain premises, from ISO/PAS 21448 (ISO, 2019) and BSI/PAS 1883 (BSI, 2020).

LIDAR				
Distortion phenomena	Guidewords	Behavior malfunction		Driving hazards
		Sensor	Vehicle	Vehicle
Measurement noise from environment	Wrong	Object could be <wrong perceived> depending on the distance [from the vehicle] to the object.	Object could be <wrong perceived> [by vehicle].	False positive: unintended activation of automatic emergency brake when it is not needed. False negative: no activation of the automatic emergency brake when it is needed

Figure 4. HAZOP example for LIDAR fault upon environment interference, adapted from (Martin et al., 2019).

Engineers may describe scene elements in the operational design domain by following a taxonomy of ODD attributes as defined by BSI/PAS 1883 (BSI, 2020), whose top-level concepts represent concrete characteristics of the SOTIF situation. Birch and colleagues (2018) approach the ODD of a driving automation feature to structure a safety argument for asserting and validating SOTIF by representing the possible situations of feature operation. Those situations include functional insufficiencies in measurement, ranging and tracking, or trigger false detections, ‘ghosts’, and errors, which may result in hazardous ego-behaviors (ISO, 2019).

2.2 Scenario formulation

In a comment to the US National Highway Traffic Safety Administration (NHTSA) about engineering practice for automated driving features, Schwalb proposes a data-driven framework with a multi-agent focus along a dynamic view about hazards regarding the use of Time-To-Incident metrics (Schwalb, 2019). Kramer et al. (2020) chime in, with stating that most ‘straight-from-the-book’ safety methods fail to include information about out-of-system factors into hazards, especially for vehicles with SAE Level 3 or above.

Besides assessing SOTIF uncertainty, Kramer and colleagues consider Risk Mitigation Measures (RMMs) to address SOTIF uncertainties alongside functional safety in four classes: (1) Functional safety measures, with improving system component reliability and Automotive Safety Integrity (ASIL) levels; (2) ODD restrictions, with reducing the scope of scenarios the system will work; (3) Behavioral safety measures, reducing exposure to environment interferences and driving hazards; and, (4) Other external measures, with improvements to traffic regulation and infrastructure under responsibility of traffic authorities. Figure 5 below displays example safety strategies to driving automation features.

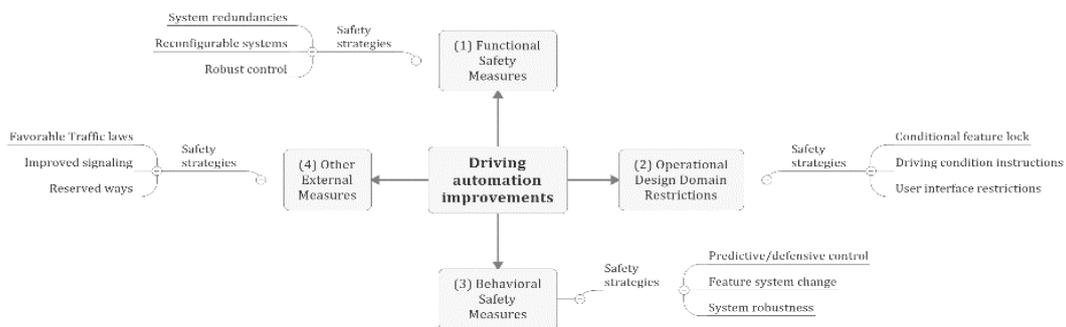


Figure 5. Courses of action to mitigate SOTIF uncertainty in driving automation features (Kramer et al., 2020).

With classes 2 and 3 falling under the scope of SOTIF improvement within the vehicle development process, RMMs to those classes can be managed under change actions through the design process, under which *post-mortem* design reviews will trigger actions to system requirements and design, component specification and implementation, integration and assembly, and then simulation/testing protocols. Such framework configures an overview about the aspects to be aware of when working with the design of driving automation features, and efforts with this goal should consider a view on how to implement awareness about them.

3. METHODOLOGY

The approach is carried out with first defining an example Operational Design Domain under which the driving automation feature for Platooning will work. Then, the research proceeds to designing a simulation protocol with specification of vehicle characteristics and driving situations as supported by the platooning driving automation feature (Mendes, 2018). The procedure completes with performing driving situations within the operational design domain, with different circumstances applied to the system dynamic model to verify the hazardous situations applicable to the operational design domain and check the following aspects: the degree to which SOTIF requirements can be assessed by the current model, and the scope of SOTIF requirements that can be derived.

The operational design domain includes a road stretch of the Dutra motorway (BR-116) spanning 110 km from the municipality of São José dos Campos/SP (km 147) to Cachoeira Paulista/SP (km 37). This makes one of the busiest transport routes in Brazil as it links the metropolises of São Paulo/SP and Rio de Janeiro/RJ, among the most populous in the country. The road stretch is built in a two-lane setup with a single emergency lane by the right, by allowing regulated vehicle speeds between 80 km/h and 90 km/h for large commercial vehicles. While there are no toll gates in the area, there are road exits to gas stations, restaurants, and neighborhoods, as well as access onramps to city bridgeways. Curvature is near-straight with the exception of a partial 16 km stretch through Aparecida and Guaratinguetá*. Table 1 displays the entry and exit points that support establishing the simulation circumstances.

Table 1. Entry/exit points by Dutra Motorway, São José dos Campos-Cachoeira Paulista.

Distance mark	147-122	122-92	92-62*	62-37
Traffic exits [@km]	146, 145	99A, 99B, 107, 111, 112, 113	65, 67, 71, 75, 81, 85	39A, 39B, 51, 53, 58
Traffic entrances [@km]	146, 145, 143A, 143B	99A, 99B, 108, 111, 112	65, 67, 71, 74, 81, 85	39A, 39B, 51, 53, 57
Speed limits [@km / km/h]		110,7 / 80	65,4 / 80	

The ODD for the simulation consists of a straight-line stretch of the motorway where the truck platoon rides by the regulated motorway speed (20 m/s), applicable for most roadway distance with exception of the curved stretch through Aparecida and Guaratinguetá*. The platoon comprises 4 (four) trucks (18.6 m length each) that keep a time gap of 1 (one) second between each other through a maximum running length of 160 m by the roadway. The scenario scope involves alternatives with one and two small vehicles (5m length each) that position themselves by the running distances between the trucks and then cut into the truck running lane within that running distance. Figure 6 shows an example display with a single small vehicle – overtaking lane on top, safety lane by the bottom.

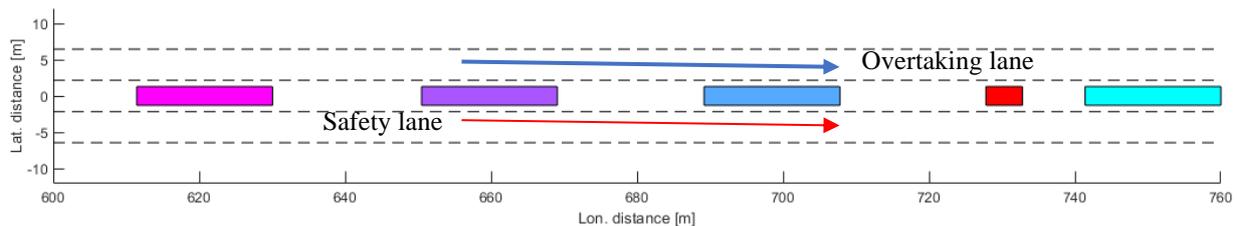


Figure 6. Example of truck platoon string with single small car entering running distance between 1st and 2nd truck.

Each small vehicle gets to run in the parallel lanes (overtaking lane and/or safety lane) at the same speed than the trucks, and then cuts into the running distance between the trucks. The simulation protocol involves the cutting in by the small vehicles at the same motorway speed than the trucks. The cutting in by small vehicles may occur in one of the following directions:

1. From the overtaking lane at the left side heading right to access the roadway exit; or,
2. From the safety lane by the right side heading left to access the roadway.

Because these vehicles ‘invade’ the running distances between the trucks, the platooning control system shall control the trucks to allow enough running distance so that small vehicles can safely exit or enter the motorway. The results display the current performance of the control system with one small car cutting in, and two small cars cutting in. The simulation protocol (Mendes, 2018) is implemented through Matlab code that commands the truck convoy of the platoon and driving actions by the small vehicles entering distance gaps between the trucks.

4. RESULTS

The results include displays of control performance through scenarios, with upper portions showing position, speed, acceleration and separation distance graphs, and lower portions showing five frames (index from 1 to 5) of each maneuver.

4.1 Single cut-in from overtaking lane between truck one (T1) and truck two (T2)

Figure 7 shows the current platooning control as being able to simulate the completion of a safe maneuver of the trucks to accommodate for loss of time gap as a result from the small vehicle cutting in between. The figure shows a single truck performing a stepwise acceleration change from detecting the vehicle, whereas others are set to smooth downramps towards recovery for the purpose of maintaining string stability. The whole platoon length tends to increase around 20 m in a 7 s timeframe – between (2) and (3), which is affordable for all attentive drivers to brake.

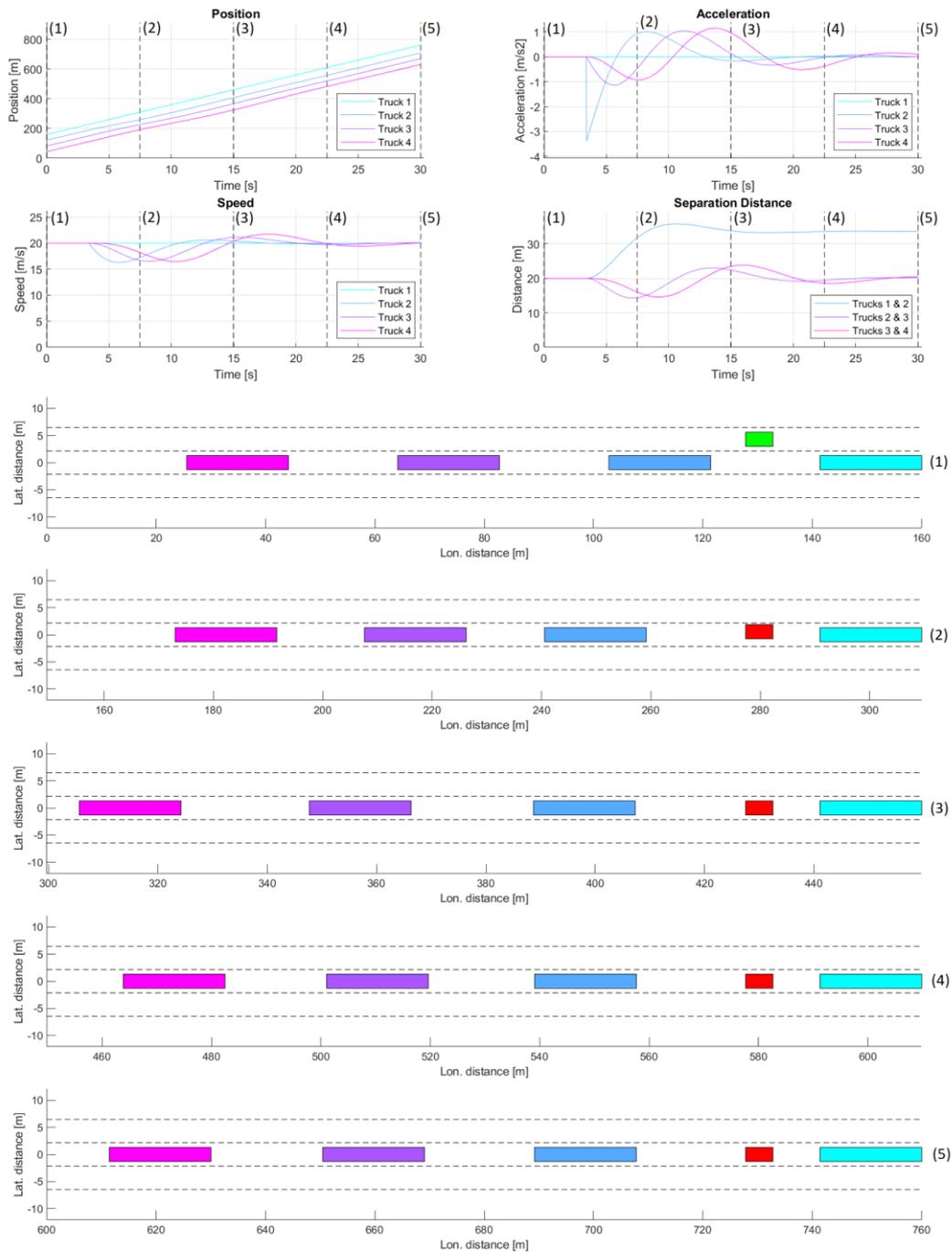


Figure 7. Response of control model to small vehicle cut-in between trucks one and two in a string stable four-truck platoon with 1 second time gap. The animation of this maneuver is available at: <https://youtu.be/5ReMLXiI8yo>

4.2 Double cut-in from overtaking lane between truck one (T1) and truck two (T2), and from safety lane between truck three (T3) and truck four (T4)

Figure 8 shows the current platooning control as being able to simulate the completion of an unsafe maneuver of the trucks trying to accommodate for loss of time gap as a result from both small vehicles cutting in between: the first from the overtaking lane between T1 and T2, and the second from the safety lane between T3 and T4. The figure shows two trucks (T2 and T4) performing a stepwise acceleration change from detecting the vehicle, whereas T3 is set to smooth downramp towards recovery for the purpose of maintaining string stability. In spite of its smooth acceleration, T3 tends to a significant movement across the platoon length, which may cause it to collide its back against the small vehicle if the latter keeps the same speed than the trucks – some accommodation is required by the small vehicle.

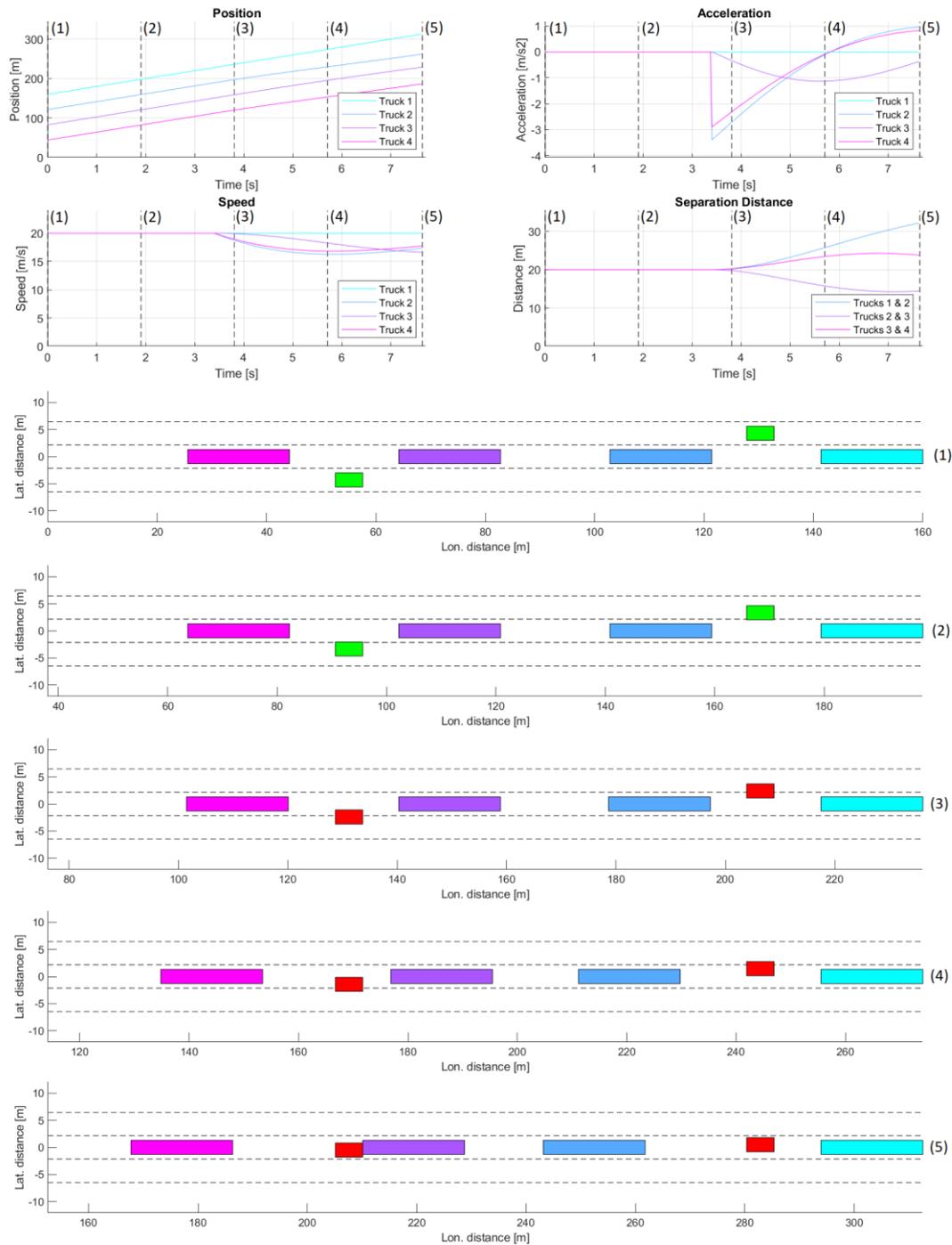


Figure 8. Response of Scenario 1 with two cut-ins to a four-truck platoon. The first cut-in occurs between trucks one and two and the second cut-in occurs between trucks three and four. Collision occurs between the rearmost car and truck 3. The animation of this maneuver is available at: <https://youtu.be/d7E10c3c-3U>

4.3 Double cut-in from overtaking lane between truck one (T1) and truck two (T2), and from safety lane between truck two (T2) and truck three (T3)

Figure 9 shows the current platooning control as being able to simulate the completion of an unsafe maneuver of the trucks trying to accommodate for loss of time gap as a result from both small vehicles cutting in between: the first from the overtaking lane between T1 and T2, and the second from the safety lane between T2 and T3. The figure shows a single truck (T2) performing a stepwise acceleration change from detecting the vehicle, whereas T3 and T4 are set to smooth downramp towards recovery for the purpose of maintaining string stability. The stepwise deceleration makes a significant movement from T2 across the platoon length, which may cause it to collide its back against the small vehicle if the latter keeps the same speed than the trucks – some accommodation is required by the small vehicle.

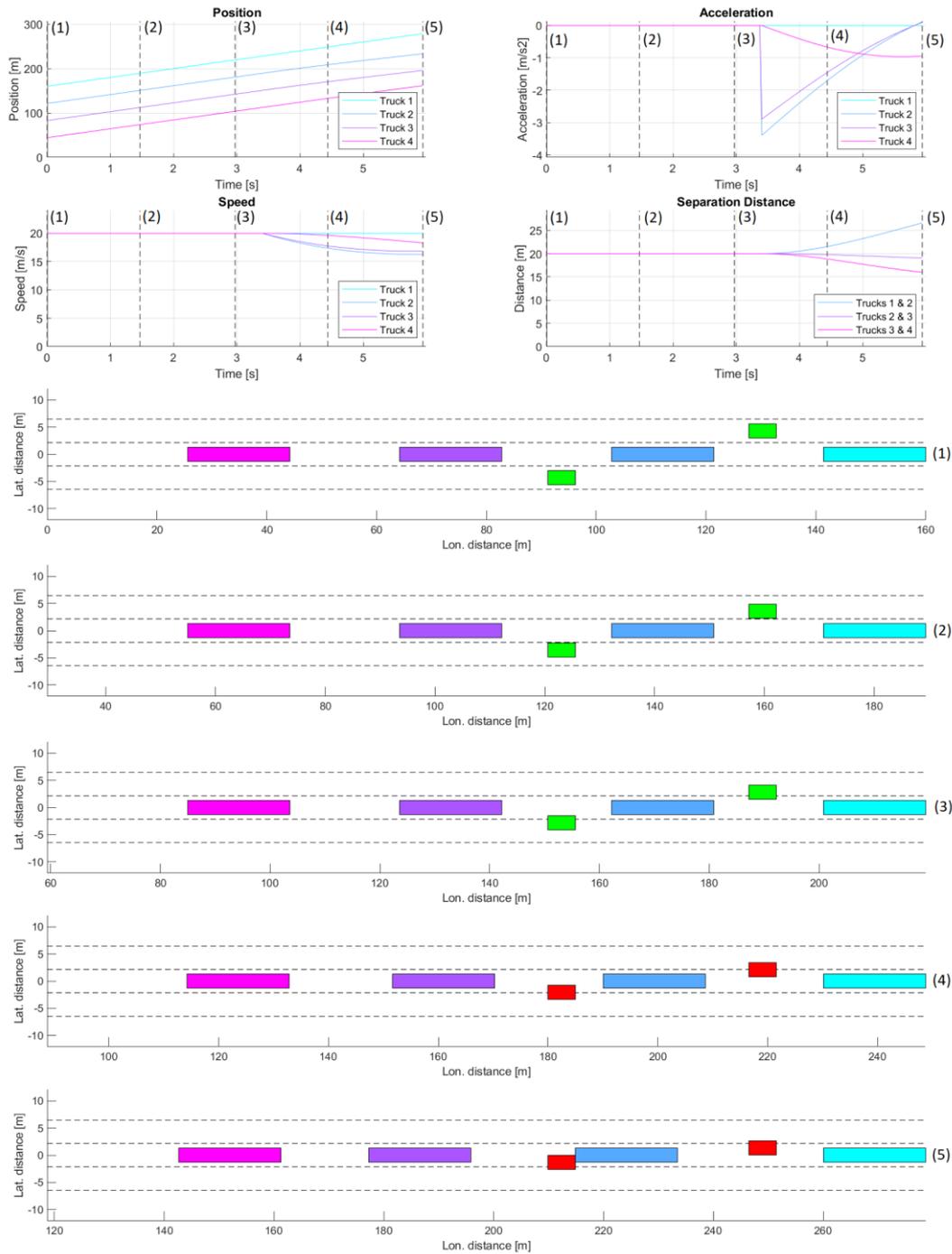


Figure 9. Response of Scenario 2 with two cut-ins to a four-truck platoon. The first cut-in occurs between trucks one and two and the second cut-in occurs between trucks two and three. Collision occurs between the rearmost car and truck two. The animation of this maneuver is available at: <https://youtu.be/7QIwht2FWVM>

4.4 Discussion of platooning control model, premises and results

The current simulation protocol considers the cut-in scenarios with one small vehicle and two small vehicles, where the small vehicles are first positioned in between the running distances between the trucks. Each of the platooning trucks has a single prismatic sensor by the vehicle width, positioned at the front, without sensing by the rear end. This single prismatic sensor is considered to operate without systemic or environment interferences. Then, small vehicles get to intrude in between the running distances at fixed longitudinal speed, as operating with a fixed speed cruise control without any adaptive support. The intruding vehicle drivers perform the manoeuvres without any attention to the truck movements in the platoon: the task for collision avoidance is placed solely on the platooning control model, which immediately performs a distance correction manoeuvre to keep the running distance to the prescribed time gap.

The control model presented in this work is sufficiently robust to accommodate for the intrusion of a single small vehicle, which requires a running distance correction around 8m for that single gap; the control model is currently set to replicate that distance correction in a smoother manner for all other running distances between trucks in the platoon. In that configuration, the control model cannot accommodate for two small vehicles intruding into the running distances between trucks. Therefore, the current configuration of the control model cannot satisfy the SOTIF objective in this case, which is the avoidance of collision between trucks and small cars while keeping string stability.

Improvements to the control model shall be considered for future work with basis on available knowledge about measures to mitigate SOTIF uncertainty (Kramer et al., 2020), guiding the use of safety methods such as in the LIDAR example (Martin et al., 2019). In specific regard to the control model, the following courses of action can work in improving the SOTIF suitability of the platooning control model, according to Figure 10:

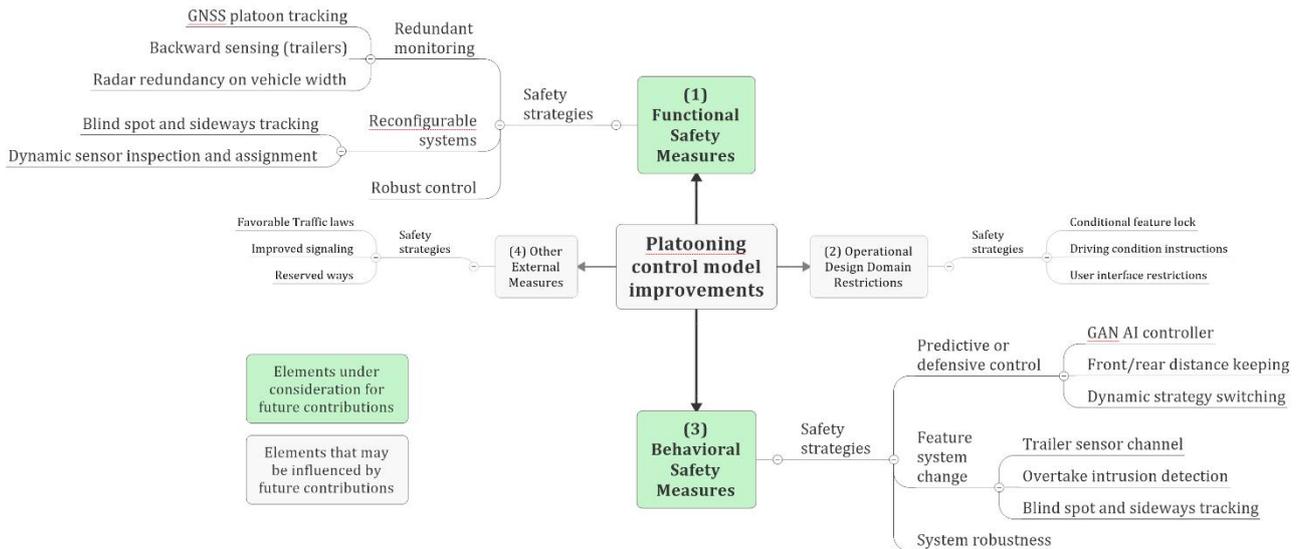


Figure 10. Courses of action applicable to mitigate SOTIF uncertainty in control model, based on (Kramer et al., 2020).

These goals can be achieved with support of further inquiry into SOTIF by our team as a design planning tool for improvements on our control model. Research is underway, which verifies sensor hardware specifications against environment interferences (Martin et al., 2019), or incorporates safety methods as frameworks for approaching driving scenarios (Kramer, 2020). Such an approach requires approaching the driving scenario as a system-of-systems, which include the truck platoon and the alien vehicles as part of a bigger system whose dynamics is described in one part by deterministic models, and in other part by estimation and/or detection models.

The figure above shows a few examples of future design improvements after the SOTIF uncertainty mitigation overview: (1a) redundant monitoring shall incorporate necessary sensors to improve the perceptual ability of the model against intrusions, such as blind spot and backward sensors, besides sideways vehicle tracking; (1b) reconfigurable systems such as sensor assignment modules shall work to reconfigure the control function upon input degradation – sensor loss, for instance; (3a) defensive control design is necessary, such as a front/rear distance keeping module that can calculate the optimal distance between all vehicles in intrusion situations; and, (3b) feature system changes involve designing an overtake intrusion detection module with basis on sequential information from blind spot and rear sensor and/or sideways tracking and front sensor, so that to enable anticipatory defensive behavior by the controlled platoon.

Besides the improvements above, we aim to improve the control model with refinements such as dynamic error estimation and control strategy switching directed by safety objectives. In a system level, dynamic modeling can be augmented with redundancy and fusion between proximity (Radar) and location (GNSS) sensor data, alongside deploying artificial intelligence (AI) approaches such as Generative Adversarial Network (GAN) algorithms. We aim to implement and test these supportive approaches in future contributions.

5. CONCLUSIONS

This work has focused on the assessment of the implications brought by the concept of SOTIF to the operation of a platoon of heavy-duty trucks in the likely event of small vehicles cut in the convoy. Simulation results show that, with a longitudinal model of the trucks dynamics and an optimal control strategy based on one prismatic radar placed at the front of each component of the platoon, potentially hazardous situations might arise in the event that two alien vehicles cut into the original convoy pattern. This suggests that, for the Dynamic Driving Task function of platooning to comply with SOTIF requirements, the issue of system robustness must be carefully considered.

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