25th ITS World Congress, Copenhagen, Denmark, 17-21 September 2018

EU-TP1382

Assessment of automated driving to design infrastructure-assisted driving at transition areas

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Abstract

When cooperative automated vehicles (CAVs) emerge on urban roads, there will be areas and situations where all levels of automation can be granted, and others where highly automated driving (AD) will not be allowed or not feasible. Complex environments, missing sensor inputs or temporary road configurations are examples of such situations and at these locations CAVs are expected to degrade their level of automation. Such geographic areas are referred to as 'Transition Areas' and presumably are associated with negative impacts on traffic safety and efficiency, in particular with mixed traffic fleets. The H2020 TransAID project is developing a digital infrastructure and dedicated traffic management strategies to assist CAVs in better anticipating to transition areas ahead, and preserve safe and smooth traffic flow.

Keywords:

AUTOMATED VEHICLES, TRANSITION OF CONTROL, INFRASTRUCTURE

Introduction

As the introduction of automated vehicles becomes feasible, even in urban areas, it will be necessary to investigate their impacts on traffic safety and efficiency. This is particularly true during the early stages of market introduction, where automated vehicles of all SAE levels (SAE International, 2016), connected vehicles (able to communicate via V2X) and conventional vehicles will share the same roads.

There will be areas and situations on the road where high levels of automation can be granted, and others where it is not allowed or not possible due to, for example, missing sensor inputs, the complexity of the situation, etc. At those locations, referred to as 'Transition Areas' (TAs), automated vehicles may initiate a change in automation level, thereby handover the control of the vehicle to the driver or perform a minimum risk manoeuvre (MRM).

The goal of TransAID is to gain insight into measures that mitigate the (possible) negative impact of unintended Transition of Control (ToC) (i.e. the handover) or MRMs on traffic flow and/or safety. Measures are envisioned with one of three goals:

1. **Prevent ToC or MRM**: Apply a solution type to a situation to prevent the ToC or MRM. The vehicle can maintain its automated driving state. As a result, the traffic flow is undisturbed.
2. **Manage or support ToC or MRM**: In some situations, a ToC or MRM might not be preventable and there is no time or space to do it elsewhere. The ToC or MRM can be managed (e.g. indicate a safe spot) and supported (e.g. inform surrounding vehicles to give way).
3. **Distribute (in time and space) ToC or MRM**: In situations where the problem is predictable, but despite the predictability ToC or MRM cannot be prevented, it is best to phase the ToC or MRM. That way, not all vehicles perform a ToC or MRM at the same time at the same place, but sequentially and distributed along the road, thereby minimizing the impact.

To design infrastructure-assisted driving at transition areas, situations in which ToC disturbs traffic need to be identified and studied. Also why, when, and where exactly ToC is triggered and if, how, where, and when it disturbs the traffic flow and/or decreases traffic safety needs to be understood. The environment, the automated driving (AD) functions and the ToC process together form the primary triggering conditions for down- or upward ToC (i.e. de- or increase the level of automation). The interrelation of these conditions is shown in Figure 1.

First those triggering conditions, or factors, will be described together with how they determine pre- and postconditions for ToC. Next, an abstraction method is presented that defines disturbance types as causes for a ToC. Thereafter, three generic solutions (as mentioned above) to cope with these disturbances are derived. Finally, based on these generic solutions five services are identified with several use cases as examples as the application of those services.

Assessment[1]

Environment

The environment is defined as everything that surrounds the automated vehicle (AV) and is thus outside that system boundary. Each change in the environment can change the vehicle behaviour and vice versa. The environment contains static, semi-static and dynamic elements.

The static elements consist of the infrastructure layout (i.e. number of lanes, intersections, merging areas, bus lanes, crosswalks, road markings, road furniture, etc.) and the elements not being part of the road infrastructure and sometimes representing obstacles to automated vehicles' sensors (i.e. buildings,

[1] This assessment is a summary of the assessment presented in TransAID deliverable 2.1 which is available on the TransAID website: www.transaid.eu

trees, foliage, etc.).

The dynamic elements consist of the presence and behaviour of surrounding vehicle types, vulnerable road users (e.g. pedestrians, bicyclists), weather conditions like rain, snow, or mist, and dynamic traffic management elements like traffic lights, VMS images, and connected and/or cooperative messages from infrastructure, service providers, and other vehicles.

Finally, the semi-static elements consist of temporary elements, for example, used for road works (e.g. pylons, truck mounted attenuators, yellow markings, barriers, additional traffic signs, etc.) or damaged infrastructure (e.g. pothole, bad road surface) that is usually repaired within days.

As said, all these elements might incur a change in the vehicle behaviour. As a result, these elements, and combinations of them, could trigger a ToC. However, the exact behaviour might depend on the automated vehicle type, for example, while in some situations an automated vehicle might require a ToC when approaching road works this might not be the case for others. As another example, there could be another group of vehicles that only need a ToC when approaching a traffic light without I2V messages.

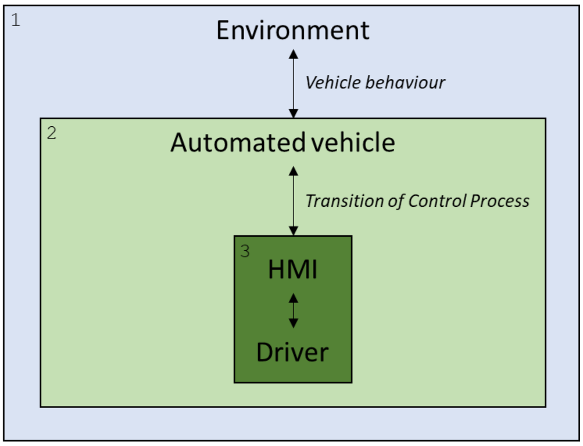

Figure 1 - Interrelation of triggering conditions for ToC

Automated driving functions

How a vehicle reacts to the environment depends on the exact implementation of the automated driving (AD) functions (indicated as area 2 in Figure 1) and the limitations of its monitoring system. In general, the AD functions determine the SAE level of driving automation (level 0, no automation to level 5, full automation). This level describes the vehicle’s high-level capabilities (e.g. automated steering, accelerating/braking, lane change capability, etc.) as well as the driver’s monitoring tasks.

All levels, except level 5, include situations where the driver must take over all or parts from the driving task from the AD system, but the parameters of these situations can be very different. For example, a level 4 vehicle might be able to cope with a road works scenario, while a level 3 vehicle might not. Also, vehicles that are capable of level 4 might change the currently active function level from level 3 to 4 when environmental conditions relax, while vehicles of another make are not capable of level 4.

Besides the high-level SAE classification, the details of the AD functions also impact the trigger conditions for a ToC and, also its effect. This impact is two-fold. On the one hand, the details determine the exact conditions prior to a ToC and thus the trigger conditions, and on the other they determine the traffic situation after a ToC.

To explain: the implemented driving distance, maximum lateral displacement with respect to lane markings, minimum/maximum acceleration and braking capability all determine the vehicle behaviour on the micro-level. Thus, vehicles that have higher braking and lateral displacement capabilities might not need a downward ToC in critical situations where the vehicle must react immediately. Contrary, those with more limited capabilities would require a ToC or MRM. Even if both types of vehicles would need a downward ToC, the resulting post-ToC traffic situations can be very different because of applying different AD parameters. Depending on this, some vehicles might execute a downward ToC and some others not.

Transition of Control process

The ToC process (indicated as area 3 in figure 1) indicates interactions between the system and the driver during an upward or downward ToC. This process is important, because during the interactions, it is expected that the driving behaviour of the car will change and thus impact its environment (e.g. other cars and traffic monitoring sensors). Because of this change, the traffic flow and/or traffic safety might improve or deteriorate. How exactly the behaviour of the vehicle changes depends on several aspects.

One of these aspects is the Human Machine Interface (HMI) design. For ToC the most important part of the HMI are the elements (i.e. signals and controls, e.g. turning AD on/off or perhaps adjust parameters like headway) that relate to automated driving functions, but other more common elements (from controls on the steering wheel to head-up displays) can be relevant as well. How exactly the vehicle signals the driver that attention is needed can differ from vehicle to vehicle and can impact the duration of the entire ToC process (Petermeijer, Cieler, & de Winter, 2017). Also, the fluidity of the ToC depends on, if whether the ToC is implemented at once or stepwise. For example, the vehicle might first give back steering control and after a few seconds signal that acceleration control is to be taken over as well.

Another aspect is the Human Factor (HF). Many studies have been done on how people respond to ToC, specifically in relation to the HMI. The most challenging situation is probably a level 3 driving automation vehicle (Gold, Naujoks, Radlmayr, Bellem, & Jarosch, 2017). At that level, most of the driving functions are performed by the vehicle and the vehicle monitors the driving environment, but the driver is expected to respond at any moment, if required. Since by definition, the driver is not required to monitor the driving environment at level 3, situation awareness is very low. It will require some time before the driver is ready to take over control, but that is only possible if time allows. Therefore, how exactly the vehicle behaves during a ToC, depends largely on the prediction capabilities of the vehicle and on the capabilities/skills and level of arousal (alertness, attention level and information processing) of the driver. Since the driver must process the state of the environment, that state is of importance as well (Gold, Körber, Lechner, & Bengler, 2016). The point just made, obviously holds for downward ToC from any level. In general, the higher the level of driving automation, the higher the engagement of the driver in secondary tasks (Naujoks, Purucker, & Neukum, 2016). This might negatively impact the driver's situation awareness and level of arousal.

Use case definition challenge

Causes for ToC or MRM can be found in all described factors. In Figure 2, the left graph shows four macro categories into which causes for ToCs (intended or unintended) as reported by OEMs were consolidated. The External condition (green), System failure (blue) and Human factors (red), roughly correspond to the Environment, AD functions and ToC process factors as presented above. The remaining category Other (yellow) are causes reported by OEMs using terminology that could not be traced to the other categories. It is important to note that the cause for sensing issues is sometimes reported as a system failure (i.e. sensor, algorithm) and sometimes as an external condition (i.e. heavy rain, snow). The other two graphs show the breakdown of the System failure and External condition categories. Each of these detailed causes potentially points to a transition area when triggering ToCs frequently in a concentrated area.

Besides any single cause being the trigger for a ToC, any combination of them might trigger a ToC as well. Subsequently, the exact effect of the ToC depends on the state of all aspects of all factors. Since any combination can result in different pre- and postconditions, in theory any combination should be considered as a separate use case.

Such an approach would result in a far too many use cases to study. Even if that number is achievable, there are many unknown aspects in each of the factors (e.g. implementation of AD and ToC functions). To tackle the many uncertainties that make it difficult to define use cases, an abstraction method is introduced to define disturbances that cause a ToC or MRM in the next paragraph.

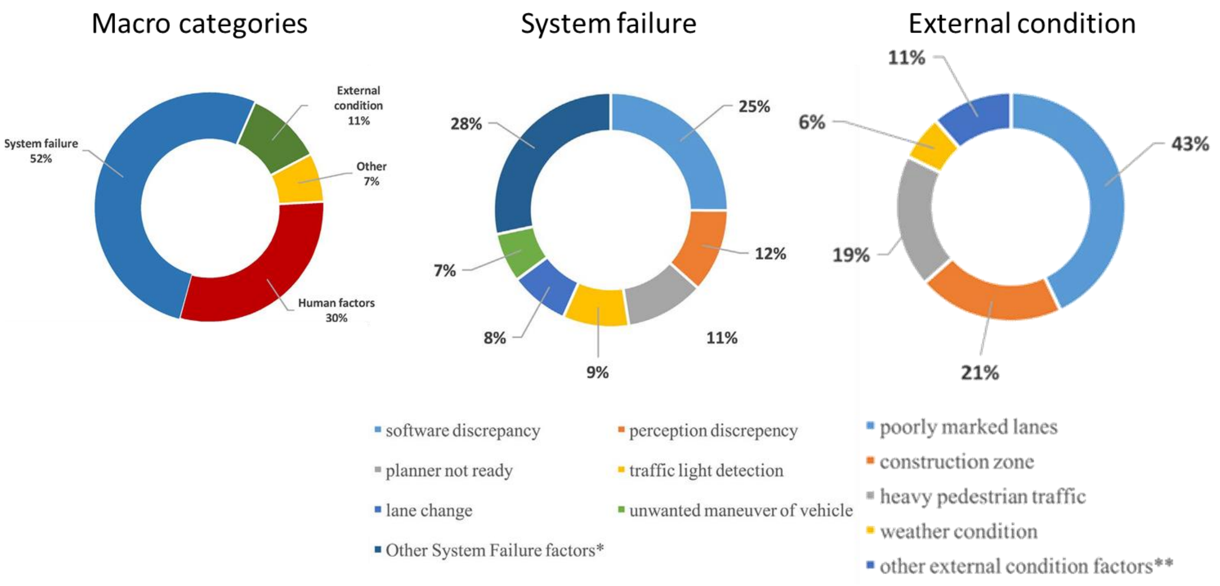

Figure 2 - Autonomous vehicles' disengagements: Trends, triggers, and regulatory limitations (Favaro et al., 2017)

Automated driving disturbances and countermeasures

Given the many uncertainties regarding the details what exactly triggers a ToC or MRM, it is useful to look to triggers or causes for ToC on a more general level to determine TransAID situations.

When looking at what is needed to perform/maintain the driving task a set of steps can be identified, which, when disturbed, are a possible cause for a ToC:

1. The vehicle needs to be aware of its environment by sensing its surroundings.
2. The vehicle needs to determine action(s).
3. The vehicle needs to perform the action(s).

If all these capabilities are supported, associated automated tasks are executed and eventually the goal is reached. However, each of these capabilities can be disturbed by the following three disturbances:

1. Environmental disturbance: the vehicle knows what to do but cannot sufficiently sense the environment. Examples are: *sensor malfunction, sensor interference (e.g. bad weather), low or sub-optimal quality of road infrastructure (absent or poor markings, temporary markings in addition to pre-existing markings at road works areas), etc.*
2. Action determination disturbance: the vehicle can sense its environment but does not know how to achieve its goal. Examples are: *exiting the motorway while deceleration lane is blocked by queue, changing lane before intersection when target lane is blocked by queue, target road is blocked and traffic laws need to be broken to pass, which way to drive when encountering unknown/new infrastructure, etc.*
3. Execution disturbance: the vehicle knows which actions to take but is incapable of executing them or cannot rely on the driver (i.e. the driving system, vehicle & driver, does not respond). Examples are: *ice on road/black ice, malfunction in vehicle (steering, braking, acceleration), unresponsive driver, etc.*

To identify situations that result in transition areas, one can look for locations where these kinds of disturbances occur more frequently. In addition, suitable (counter)measures that mitigate the mentioned disturbance types can be identified as follows:

1. Provide environmental information. Examples of this information are: *digital map, position of other vehicles/objects/vulnerable road users, etc.*
2. Determine action (i.e. enable an action or suggest a different action). For example: *instruct vehicles in a queued lane to leave a gap for the vehicle that has that lane a its target lane, instruct the vehicle to move to end of the queued lane, suggest to cross a solid line, etc.*
3. Manage the environment. In this case, not much can be done for the vehicle or driver itself, but from a traffic management perspective, warnings or actions for the other vehicles can be provided to minimise the impact of the incapacitated vehicle. For example: *sending warnings from a vehicle performing a MRM to other vehicles directly from the incapacitated vehicle and via road side infrastructure.*

To summarise, the provided disturbances and countermeasures provide a first insight into which situations potentially result in transitions areas and a rough indication of how to cope with unintended ToCs in automated vehicles.

Solution implementation

Based on the aforementioned ToC factors, AD disturbances and possible countermeasures, the TransAID partners started to define initial transition area situations and propose suitable solutions. This resulted in a list of use cases with situations, solutions and their properties with varying levels of details. By studying this list, it was found there are three generic solutions as described above in the introduction: Prevent ToC/MRM, Manage or support ToC/ MRM or Distribute (in time and space) ToC/MRM.

It was also observed that the resulting use cases could be grouped in use cases categories associated with common measures as implementation of these solutions. Five "services" defined as use case categories were identified:

1. Prevent ToC/MRM by providing vehicle path information
   To prevent ToCs/MRMs, detailed information is provided about the path a CAV should take.
2. Prevent ToC/MRM by providing speed, headway and/or lane advice
   This service provides speed, headway and/or lane advice to vehicles to prevent a ToC/MRM due to complex traffic situations emerging from either planned or unpredictable events.
3. Prevent ToC/MRM by traffic separation
   Different vehicle types (CAV, AV, CV, LV) are separated by giving lane advice per type before critical situations. Vehicle interactions are reduced to reduce the chance of ToCs/MRMs and thus prevent those.
4. Manage MRM by guidance to safe spot
   In case a vehicle is going to perform a MRM, infrastructure helps by providing detailed information about possible safe stops.
5. Distribute ToC/MRM by scheduling ToCs
   Whenever multiple ToCs need to be executed in the same area, this service distributes them in time and space to avoid collective ToCs and possibly MRMs in a small area.

These five services serve as generic solutions to prevent issues around transition areas. Depending on the cause for ToCs one or more of these services can be applied to the situation to mitigate negative impact of ToCs.

Use cases and scenarios

Within the services TransAID has defined several use cases (14 in total, see Table 1) and scenarios. Note that the listed use cases are not an exhaustive list of all possible use cases, but a set of examples. The services could be applied to many other situations, thereby creating additional use cases.

Of the defined scenarios, five have been selected (underlined in Table 1 and shown in Figure 3) for further study trough simulation and real-world experiments. Timelines for these use cases and requirements regarding the vehicle modelling, communication and traffic measures have been created and are currently being worked out into more detail. Below the five scenarios are briefly introduced.

Table 1 – Overview of TransAID use cases grouped by service

Service 1	**Service 3**
1.1 Provide path around road works via bus lane	3.1 Apply traffic separation before motorway merging/diverging
1.2 Provide path around stopped vehicle via bus lane	3.2 Apply traffic separation before motorway on-ramp
1.3 Provide path to end of queue on motorway exit	3.3 Apply traffic separation before roadworks areas
Service 2	**Service 4**
2.1 Prevent ToC/MRM at motorway merge segments	4.1 Safe spot outside carriageway
2.2 Prevent ToC/MRM at motorway merge segments (CAV Platoon)	4.2 Safe spot in lane of blockage
	Service 5
2.3 Intersection handling due to incident	5.1 Schedule ToCs before no AD zone
2.4 Intersection handling due to road works	5.2 Schedule ToCs after no AD zone

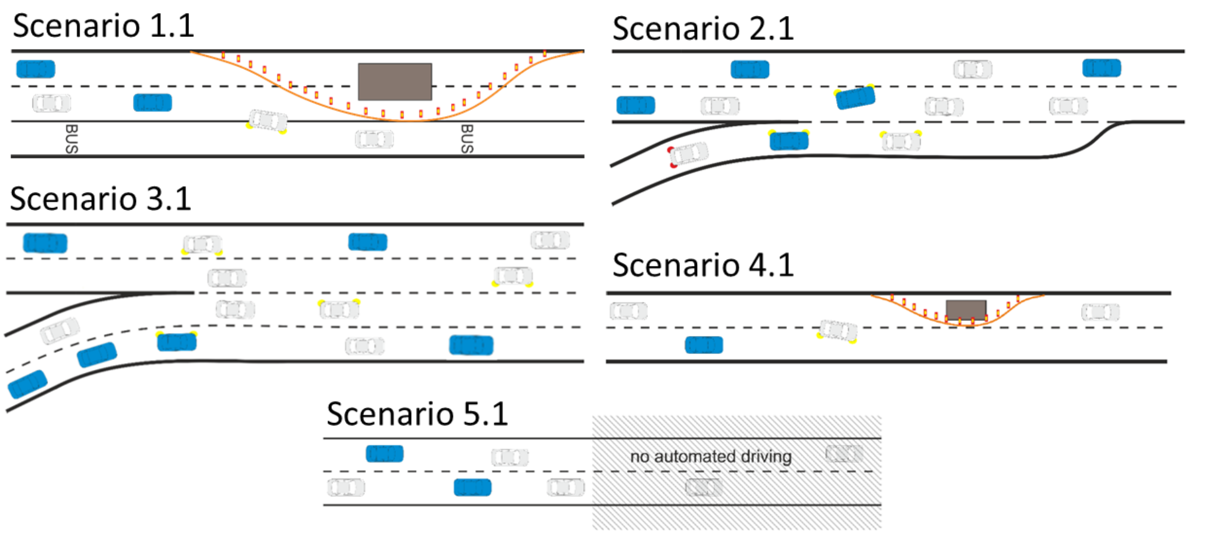

Figure 3 – Overview of the five selected scenarios

Scenario 1.1 - Provide path around road works via bus lane

In most situations where road works block the normal lanes and there is a bus lane, that lane is provided as an alternative route to circumvent the road works. Automated vehicles might not have the (appropriate) logic to determine whether such an action is tolerated in the given situation (i.e. unable to detect the situation and corresponding correct lane markings) and need to perform a ToC. Also, especially in urban situations, such markings might not always be provided (in every country). By explicitly providing a path around the road works from the road side infrastructure (RSI), CAVs (shown in blue in Figure 3) can drive around the road works and maintain their automated driving (AD) mode (and thus preventing a ToC). That way, it is clear where the CAV is allowed to break the traffic rules and drive across the bus lane.

Scenario 2.1 - Prevent ToC/MRM at motorway merge segments

Vehicles, including CAVs, drive along a motorway merge segment or enter the mainline motorway lanes through an on-ramp (see Figure 3). The RSI monitors traffic operations along the motorway merge segment and detects the available gaps on the right-most mainline lane to estimate speed and lane advice for merging cooperative vehicles coming from the on-ramp. If the available gaps are not large enough to allow the safe and smooth merging of on-ramp vehicles, speed and lane advices are also provided to the cooperative vehicles driving on the main road, thereby creating the necessary gaps in traffic to facilitate the smooth merging of on-ramp vehicles.

Scenario 3.1 – Apply traffic separation before motorway merging/diverging

Vehicles, including CAVs, drive along two 2-lane motorways that merge into one 4-lane motorway (see Figure 3). After the merging point, vehicles will drive to their target lane. Based on the provided traffic separation policy, CAVs and CAV platoons move to the left lane of the left 2-lane motorway and to the right on the right 2-lane motorway at some point upstream of the merging point (where merging usually starts). Other cooperative vehicles move to the other lanes not allocated to CAVs and CAV platoons. CAVs and CAV platoons thus enter the 4-lane section on the outer lanes, giving space to manually driven vehicles to occupy the central lanes. Following this approach, the overall number of risky situations due to human behaviour will be reduced which will reduce the number of ToCs in this area.

Scenario 4.2 – Safe spot in lane of blockage

There is a construction site covering one lane of the motorway road. The RSI has information about the construction area and the vicinity of it and provides this information to the approaching CAVs. Some CAVs are not able to pass the construction site without any additional guidance. Therefore, they need to perform a ToC. A ToC might be unsuccessful and then the respective CAV must perform an MRM. Without additional measures, the CAV would simply brake and stop on the lane it is driving, most likely disrupting the traffic flow, especially if this occurs on the right lane (see Figure 3). To avoid this, the RSI also monitors the area just in front of the construction site and offers this place as a safe stop to the vehicle, if free. The CAV uses the safe spot information just in front of the construction site to come to a safe stop in case of an MRM.

Scenario 5.1 – Schedule ToCs before no AD zone

After and during a ToC, an automated vehicle is expected to behave more erratically. The driving characteristics are different (e.g. different headway, different lateral movement variation, different overtaking behaviour, etc.). Because the driving behaviour during transitions and driving behaviour shortly thereafter are different, traffic flow and safety are disturbed. This effect is amplified when there are many ToCs in the same area. To prevent that amplification, ToCs are distributed in time and space upstream of an area where there is no or limited automated driving (e.g. tunnel, geofence, complicated road works). Figure 3 shows the Scenario 5.1 where CAVs and other traffic are approaching a no AD zone with 2 lanes. Starting at some point upstream of the no AD zone, the RSI determines the positions and speeds of vehicles and determines the optimal location and moment for CAVs to perform a ToC. Subsequently, ToC requests are provided to the corresponding CAVs. Based on those requests, the CAVs perform ToCs at the desired location and moment in time. Other cooperative vehicles are warned about the ToCs and possible MRMs. In the no AD zone, the CAVs are in manual mode.

Conclusions and next steps

Although CAV capabilities are being constantly enhanced, there are numerous conditions that require driver intervention to the primary driving tasks. Complex traffic conditions, weather events, work zones, CAV system breakdown, or infrastructure malfunction might incur a downward automation level change by means of a take-over request to the driver. In case the driver is irresponsive the CAV might further initiate a Minimum Risk Manoeuvre based on its systems capabilities which is highly likely to negatively impact safety and traffic operations.

To identify situations with those conditions, TransAID has looked to state of the art literature, held a workshop with road authorities, consulted advisory board members and interviewed experts. The findings have been combined to identify the relevant aspects for TransAID scenarios and Transition of Control (ToC) in general. These aspects were grouped into three classes: Environment, Automated Driving Functions and the Transition of Control Process.

The large number of aspects affecting automated vehicle behaviour and possible trigger conditions in combination with the many uncertainties regarding those aspects and conditions, posed a challenge to determine which variables exactly compose a TransAID situation. We therefore needed a generic approach that works more or less independent of those variables.

As a solution TransAID has defined five generic services preventing, managing or distributing ToC or Minimum Risk Manoeuvres, which can be applied to many situations, thereby creating use cases.

Five of these use cases have been selected for further study trough simulation and real world experiments. Timelines for these use cases and requirements regarding the vehicle modelling, communication and traffic measures have been created and are currently being detailed.

Acknowledgments

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 723390. The consortium consists of: Deutsches Zentrum für Luft- und Raumfahrt (DLR), Dynniq UK, Hyundai Motor Europe Technical Center, MAP Traffic Management, Transport & Mobility Leuven, University Miguel Hernandez de Elche and Centre for Research and Technology Hellas.

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