Management of Transitions of Control in Mixed Traffic with Automated Vehicles

Alejandro Correa [a], Sven Maerivoet [b], Evangelos Mintsis [c], Anton Wijbenga [d], Miguel Sepulcre [a], Michele Rondinone [e], Julian Schindler [f], Javier Gozalvez [a]

[a] Universidad Miguel Hernandez de Elche, Elche, Spain, {acorrea, msepulcre, j.gozalvez}@umh.es

[b] Transport & Mobility, Leuven, Belgium, sven.maerivoet@tmleuven.be

[c] Hellenic Institute of Transport, Centre for Research and Technology Hellas, Greece, vmintsis@certh.gr

[d] MAP Traffic Management, The Netherlands, anton.wijbenga@maptm.nl

[e] Hyundai Motor Europe Technical Center, Germany, MRondinone@hyundai-europe.com

[f] German Aerospace Center (DLR), Germany, Julian.Schindler@dlr.de

Abstract— **Automated vehicles can currently drive in different traffic conditions, but there still exist situations that automated vehicles cannot handle efficiently and safely. When an automated vehicle reaches its functional system limits or encounters unexpected situations, a transition of control is needed to handover vehicle control to the driver. A transition of control requires that the driver obtains the full situation awareness and takes control of the primary driving tasks. Transition of control is expected to negatively impact traffic efficiency and safety. The latter impacts will be especially relevant in areas where multiple automated vehicles need to perform a transition of control simultaneously. To efficiently and safely deal with multiple transitions of control, novel traffic management measures are needed. These measures should take into account not only the automated vehicles, but also the overall traffic stream. This paper proposes different traffic management measures supported by C-ITS and designed to handle transitions of control in mixed traffic scenarios, where automated, connected and conventional vehicles coexist.**

Keywords—Connected automated driving, transitions of control, traffic management, mixed traffic, transition areas, cooperative driving, V2X communications, C-ITS.

I. INTRODUCTION

Automated Vehicles (AV) are envisioned to improve the traffic flow and reduce road fatalities thanks to their improved perception and driving capabilities. AVs are being designed to drive highly automated in diverse traffic conditions in the future. However, different studies have shown that automated driving will not be possible in all situations and therefore Transitions of Control (ToC) will be required [1]. ToCs are triggered to handover the control of the vehicle to the driver, or vice versa. ToCs are necessary whenever the automated mode reaches its functional system limits and cannot handle a traffic situation by its own (downward ToC). They are also needed when, for example, the automated driving mode detects that the human driver does not respond or is unable to avoid a traffic accident (upward ToC).

Most of the studies conducted to date focus on the analysis of the human driver reaction during a ToC [1]. Once a ToC is triggered, the human driver needs to obtain full situation awareness before taking control of the vehicle. In general, it has been found that the higher the level of automation the longer the duration of the ToC [2]. Highly distracted human drivers need more time to regain situation awareness and take over vehicle control [3]. Other authors focus on the reaction of human drivers in high traffic density situations [4][5], showing that the time-to-collision is reduced and the number of accidents is increased as the complexity increases.

Related studies investigate the effect of ToCs on the driver of the ego-vehicle. However, a ToC will also negatively impact the surrounding traffic flow and safety. These negative effects will be particularly relevant in areas where multiple ToCs can frequently occur in a relatively small time window, which we will refer to as Transition Areas. In this context, to the best of the authors' knowledge, this paper presents the first set of traffic management measures that are designed to minimize the negative effects of ToCs in Transition Areas. This work is conducted under the framework of the H2020 TransAID (Transition Areas for Infrastructure-Assisted Driving) project [6]. TransAID is focused on the development of cooperative traffic management measures for ToCs in mixed traffic scenarios where automated, connected, and conventional vehicles coexist. To this aim, TransAID uses C-ITS, i.e. cooperative ITS for V2X communications. The infrastructure and vehicles use C-ITS to extend their perception and knowledge of the environment. C-ITS will also be used to support the execution of cooperative maneuvers that will help a smooth management of ToCs. In this context, this paper proposes the first measures to manage ToCs considering the overall traffic stream, and not only the ego-vehicle. Different measures have been defined for different scenarios with different ToC triggering conditions. All measures are valid for mixed traffic scenarios where automated, connected and conventional vehicles coexist.

The remainder of this paper is organized as follows. Section II covers the analysis of transitions of control. Section III describes the approach of the TransAID project. Section IV presents the first set of traffic management measures for Transition Areas. Finally, Section V presents the main conclusions obtained and future work.

II. TRANSITIONS OF CONTROL

A transition of control is defined as the process of changing from one static state of driving to another static state [2]. There are different states of driving depending on who (the driver or the vehicle) is in charge of the longitudinal and lateral control of the vehicle and who is monitoring the environment [2]. A ToC can be an upward ToC when the

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control is relinquished to automated driving or a downward ToC when control returns to the human driver. In this paper, we focus on the study of downward transitions of control (any further mention of ToC will refer to downward ToC unless otherwise stated). Transitions of control are mainly affected by three factors: the automated driving capabilities, the human factor and the environment.

The automated driving capabilities define the behavior of the vehicle when the automated driving mode is engaged. In a complex situation, the specific automated driving capabilities of an AV will determine if the vehicle can maintain the automated driving mode or if a ToC is needed.

The human factor is defined as the reaction of a human driver during a transition of control. Once a ToC is triggered, the human factor will impact the driving behavior of the vehicle during and shortly after the transition of control [1]. The human factor is conditioned by the design of the Human Machine Interface (HMI). The HMI determines the signaling between the vehicle and the driver. Thus, it determines how exactly the vehicle signals the driver that attention is needed before a ToC. Note that, in a ToC the driver needs to obtain full situation awareness. Therefore, the duration of the ToC will be influenced by the way the driver is alerted [7]. Furthermore, if the human driver does not respond to a ToC, the vehicle will trigger a Minimum Risk Maneuver (MRM). A MRM is a controlled stop, usually at the ego-lane, and can affect the overall traffic flow and safety.

The environment is defined as everything that surrounds the AV. Thus, elements like surrounding vehicles on the road, the weather conditions, or the road markings are part of the environment of an AV. Changes in the environment can alter the vehicle behavior and vice versa. For example, if the preceding vehicle slows down, the ego-vehicle will need to slow down or perform a lane change.

Fig. 1 shows the different phases of the ToC of an automated vehicle. As it can be observed, once the ToC is triggered, the system needs certain time to ensure that the driver has full situation awareness before starting the manual driving.

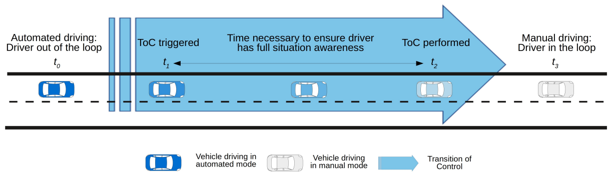

Fig. 1. Impact of transitions of control in a Transition Area

Transitions of control affect not only the ego-vehicle but, also nearby vehicles, even when a single ToC occur in a certain traffic situation. During a ToC, the behavior of the vehicle is changed. Thus, surrounding vehicles might need to modify their driving parameters in order to adapt to the change in their environment. Similarly, the vehicle performing a ToC will need to react to sudden changes in its environment. This can be problematic in mixed traffic scenarios where conventional vehicles can perform unpredictable maneuvers (i.e. sudden/delayed merging, cut-offs, quick take overs, etc.). For these reasons, a ToC negatively influences the traffic efficiency and safety.

In Transition Areas the negative impact of transitions of control is magnified because multiple ToCs occur at nearly the same time. Consequently, vehicles need to react to multiple changes in their environment, which in turn can produce new changes in the environment and therefore trigger additional ToCs. Fig. 2 shows an example of the impact of ToCs in a Transition Area. In Fig. 2a, two non-automated vehicles overpass a road works area using the bus lane. In this case, drivers manually change the lane and are able to smoothly overpass the road works area. In Fig. 2b, two Cooperative Automated Vehicles (CAVs) approach the road works area. CAVs are not able to identify the proper route to overpass the road works area. As a result, they perform a ToC just before the lanes are blocked. In this case there is no traffic

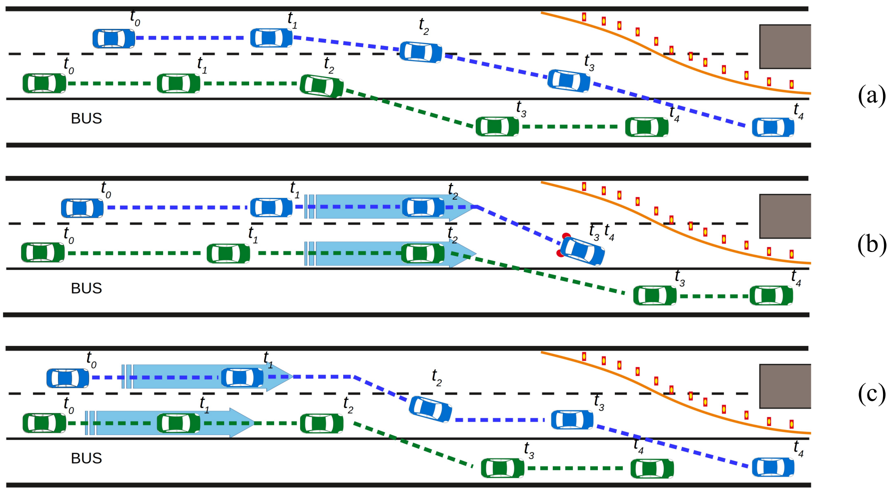

Fig. 2. Impact of transitions of control in a Transition Area

management measure applied to handle the ToC. The blue CAV does not have enough space to perform the lane changes needed and has to decelerate, which will negatively impact the traffic flow and safety. Fig. 2c shows how the application of traffic management measures to handle the ToC can improve the traffic flow and safety compared to the second subfigure. In the third subfigure, CAVs perform the ToC upstream of the road works thanks to the application of a traffic management measure that distributes the ToC in time and space to avoid multiple ToC in the same area. Thus, the vehicles have enough space to handover the control to the driver. Drivers manually execute the necessary lane changes and are able to smoothly overpass the road works area.

This example has shown how the interactions between vehicles in a Transition Area can create unstable, unsafe and inefficient situations. Therefore, it is necessary to define traffic management measures for Transition Areas that take into account the effects of ToCs on the overall traffic stream. Fig. 3 shows a Transition Area where multiple ToCs occur including examples of how ToCs impact the traffic flow. Unexpected lane changes of manually driven vehicles after a ToC, speed changes during or after a ToC, or lane changes of human drivers while some CAVs are performing ToCs are some of the examples illustrated in this figure.

The traffic management measures to deal with ToCs in Transition Areas will significantly benefit from vehicles equipped with V2X communications. Connected Vehicles (CV) and CAVs will be key to reduce the negative effect of ToCs in Transition Areas thanks to their capability to exchange information in real-time using wireless communications. On one hand, CVs and CAVs will be able to exchange information about their environment so that they cooperatively improve their perception capabilities. On the other hand, they will be able to coordinate their maneuvers before, during and after ToCs.

III. TRANSAID APPROACH

The H2020 TransAID project [6] aims at developing and demonstrating cooperative traffic management measures to enable the smooth coexistence of automated, connected, and conventional vehicles, especially at Transition Areas. One of the goals of the TransAID project is the development of infrastructure-assisted traffic management measures to reduce the negative impacts of ToCs in Transition Areas. A hierarchical approach is followed where control actions are implemented at different layers including centralized traffic management, infrastructure, and vehicles. In TransAID, we have defined three approaches to handle multiple ToCs in Transition Areas and minimize their impact on traffic flow and safety [8]:

Prevent ToC: the overall traffic situation is analyzed and a traffic management measure is defined to maintain the automated driving level of CAVs. As a result, the traffic flow is not disturbed.

Distribute ToC: in situations where the problem that causes the ToC is predictable, but the ToC cannot be prevented, the ToCs are distributed in time and space to avoid multiple ToCs in the same area.

Manage ToC: when ToCs cannot be avoided and there is no time or space to distribute ToCs, this approach is employed to support CAVs during the execution of the transitions of control.

The TransAID project defines 5 services by utilizing the previous approaches [9] (see Table I). In TransAID, a service is a traffic management measure to handle multiple ToCs that can be applied to different scenarios.

TABLE I. TRANSAID TRAFFIC MANAGEMENT SERVICES [9]

Name of the Service	*Description*
Service 1: Prevent ToC/MRM by providing vehicle path information.	Provide path information to CAVs that cannot maintain the automated driving mode due to inherent logic limitations.
Service 2: Prevent ToC/MRM by providing speed, headway and/or lane advice.	Provide designated speed, headway and/or lane advices to facilitate maneuvers.
Service 3: Prevent ToC/MRM by traffic separation.	Guide CAVs to dedicated lanes to limit vehicle interaction and prevent ToC/MRM.
Service 4: Manage MRM by guidance to safe spot.	Guide CAVs to safe stop spot where traffic flow and safety are minimally impacted.
Service 5: Distribute ToCs by scheduling ToCs.	ToCs are distributed in time and space to prevent traffic disturbance due to collective ToCs.

In the TransAID project, the role of the infrastructure is to collect information about the environment, define the traffic management measures and disseminate the measures to the traffic stream. The collection of information about the traffic stream is required to define the parameters of the service, which can depend on, for example, the level of service or the traffic stream composition. The level of service evaluates the service quality of a road perceived by the drivers [10]. The traffic stream composition is the share of different type of vehicles according to their automation capabilities. This information can be obtained from road sensors, which provide information to the infrastructure about the traffic stream. Moreover, it can also be obtained from connected (automated) vehicles, which transmit information about themselves and can also share information about the environment.

All services require the definition of the Service Area, which is defined as the area where the service is applied. The

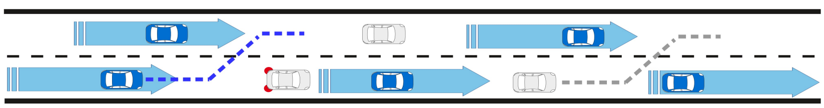

Fig. 3. Example of the impact of multiple transitions of control in a Transition Area

Service Area and the Transition Area can be different because some services might need to start managing the traffic upstream of the Transition Area. An example of this is shown in Fig. 4 where a Distribute ToC measure is applied before an area where it is not possible to drive autonomously. In this case, an area larger than the Transition Area is needed in order to distribute the ToCs of all the AVs (depicted in blue). Thus, the Service Area is extended upstream of the Transition Area.

The dissemination of the traffic management measures to the entire traffic stream is done employing two different methods depending on the connectivity of the vehicles. Connected vehicles can receive the measures employing I2V communications. Conventional signaling such as variable message signs must be employed to communicate with non-connected vehicles.

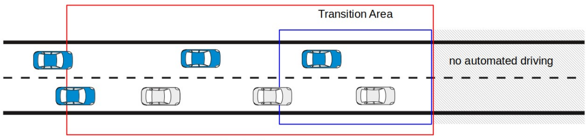

Fig. 4. Transition Area and Service Area

IV. TRANSAID SERVICES

This section describes in detail the services defined in the TransAID project for managing the traffic and reduce the negative impacts of multiple transitions of control. For each service, a representative scenario of application is described and the timeline for the deployment of the service in that scenario is detailed.

A. Service 1: Prevent ToC/MRM by providing vehicle path information

There are situations where an obstacle blocks one or more lanes of a road (i.e. due to road works, an accident, a fallen tree, etc.). Human drivers can easily overcome these situations by identifying and selecting an alternative route. However, these situations can be challenging for CAVs because they need to identify an alternative route in order to overpass the obstacle. These situations are especially challenging if the alternative route implies the temporary use of an area designated for other uses (i.e. driving across a bus lane, bicycle lane or side walk). Automated vehicles might not have the appropriate logic to determine whether such an action is allowed or not in all possible situations. Multiple ToCs will be therefore initiated to handover the control to the driver, thus degrading the traffic safety and efficiency in the area. Service 1 addresses this problem and prevents the ToCs by providing a path around the obstacle to all approaching CAVs. CAVs will therefore be able to maintain their automated driving mode avoiding a ToC that will impinge the traffic flow.

Fig. 5 illustrates a scenario where Service 1 can be applied. In this case, a two-lane road with a bus lane next to it is blocked by a road works area. In this scenario, it is assumed that the infrastructure has planned an alternative path and is distributing it. Consequently, approaching CAVs (depicted in blue) receive the path and use it to smoothly drive around the road works area avoiding a ToC. Note that Service 1 can be applied to other scenarios with minor modifications like for example modifying the type of blockage of the road (i.e. an accident, a fallen tree, etc.) or the type of restricted area (i.e. emergency lane, bicycle lane, etc.).

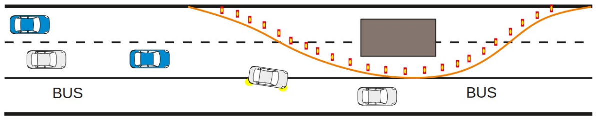

Fig. 5. Scenario where Service 1 can be applied [9]

In Service 1, the geographical limits of the path depend on the level of service of the road. When the level of service is above a predefined threshold, the starting point of the path is defined at some point upstream of the road works. From this point downstream, the upcoming vehicles can merge to the bus lane. However, when the level of service is below the predefined threshold the starting point of the path is defined close to the road works to employ a traffic efficiency measure where the vehicles remain in their lanes and merge just before the road works. In this situation, vehicles will drive in the same lane until the merging point of two lanes. Then vehicles in the left-most lane will merge to the right lane. Vehicles on the right lane will create space gaps to facilitate the merging of vehicles. Note that vehicles driving in the left-most lane will need to repeat the process twice: first to merge to the right lane and second to merge to the bus lane. The following timeline describes the sequence of actions that need to be performed to deploy Service 1 in the scenario illustrated in Fig. 5.

TIMELINE OF SERVICE 1

```
Collect information about traffic stream
Calculate level of service
Define Service Area
If level of service>threshold then
  Define starting point upstream of road works
  Disseminate measures to the traffic stream
  For each connected vehicle or CAV do
    Estimate gap for merging to right lane
    If gap large enough then
      Initiate lane change
    Else
      If there are CAVs nearby then
        Initiate cooperative lane change
      Else
        Return 8
      End if
    End if
    If vehicle is on the bus lane then
      Follow the path to overpass road works
    Else
      Keep driving in the same lane
      Return 8
    End if
  End for
Else
  Define starting point close to road works
  Disseminate measures to the traffic stream
  For each connected vehicle or CAV do
    If vehicle is at merging point then
      If vehicle is on left lane then
        Instruct to merge to the right lane
        Estimate gap for merging to right lane
        If gap large enough then
          Initiate lane change
        Else
          If there are CAVs nearby then
            Initiate cooperative lane change
```

```
          Else
            Return 32
          End if
        End if
      Else
        Instruct to leave space gaps for left
         lane vehicles
      End if
    Else
      If vehicle is on the bus lane then
        Follow the path to overpass road works
      Else
        Keep driving in the same lane
        Return 29
      End if
    End if
  End for
End if
```

B. Service 2: Prevent ToC/MRM by providing speed, headway and/or lane advice

In areas with a high number of vehicle interactions, traffic turbulences or shockwaves can be produced. As a result, CAVs might trigger ToC or execute MRMs. For example, in highway merging areas or in traffic incidents. To reduce traffic turbulence and ensure safe and efficient traffic operations, speed and lane advices can be provided through V2X communications. The reduction of the number of unexpected situations that a CAV may encounter will potentially decrease the number of ToCs and MRMs.

The schematic overview of a scenario where Service 2 can be deployed is depicted in Fig. 6. This scenario considers an on-ramp lane and a two-lane motorway. The infrastructure monitors the traffic operations along the merge segment. Then, it estimates the available gaps in the right-most lane of the motorway that can be used for the merging of on-ramp vehicles. It also estimates the required gaps that will be necessary in order to allow the smooth and safe merging of the on-ramp vehicles. Afterwards, it provides speed and lane advices to the connected vehicles to exploit the already available gaps or generate new required ones. Service 2 can be applied to other complex traffic situations, as for example complex intersections or complex traffic interactions involving platoons.

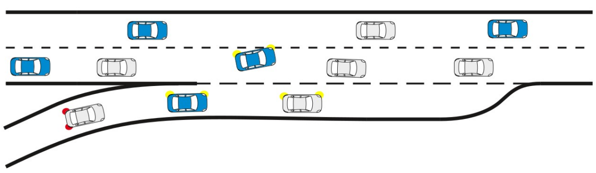

Fig. 6. Scenario where Service 2 can be applied [9]

The following timeline describes the sequence of actions that is needed to apply Service 2 in the scenario depicted in Fig. 6.

TIMELINE OF SERVICE 2

```
Collect information about traffic stream
Calculate level of service
Define Service Area
Estimate the number of required gaps
Estimate the number of available gaps
If Level of service>threshold then
  If required gaps>available gaps then
    Compute speed and lane advice
    Disseminate advices to connected vehicles
    For each connected vehicle or CAV do
      Acquire target speed
      If lane change needed then
        Estimate gap for merging
        If gap large enough then
          Initiate lane change
        Else
          If there are CAVs nearby then
            Initiate cooperative lane change
          Else
            Return 13
          End if
        End if
      End if
    End for
  End if
End if
```

C. Service 3: Prevent ToC/MRM by traffic separation

The interactions between automated and non-automated vehicles can also negatively affect the efficiency and safety of traffic. Non-automated vehicles can create dangerous situations due to the unpredictable behavior of human drivers in certain situations. In these situations, the likelihood of a CAV performing a ToC or MRM is higher. A possible solution for managing the coexistence of automated and non-automated vehicles in such critical situations is to separate them over different sectors of the road. This will reduce the number of interactions between automated and non-automated vehicles. Consequently, the number of potential ToCs will be reduced.

Fig. 7 shows a scenario where Service 3 can be applied. It considers two two-lane motorways merging in a four-lane motorway. The infrastructure disseminates a traffic separation measure where the automated vehicles are advised to move to the outermost-lanes and the non-automated vehicles are advised to move to the inner lanes. As a result, the interaction between automated and non-automated vehicles is minimized in the middle lanes, where dangerous human-initiated maneuvers can occur (e.g. sudden/delayed merging, cut-offs, quick take overs, etc.). Thus, the risk of ToC due to (risky) interactions is reduced. Service 3 can be applied to other scenarios with a high number of interactions between automated and non-automated vehicles (i.e. road works areas, diverging motorways, etc.).

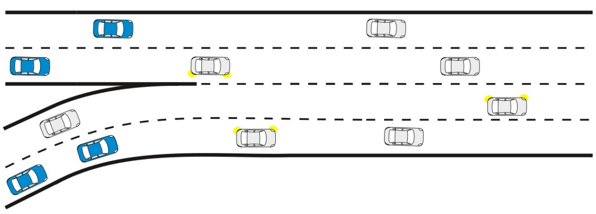

Fig. 7. Scenario where Service 3 can be applied [9]

Service 3 requires the collection of information about the traffic stream composition in order to be able to distinguish between automated and non-automated vehicles. This service must also know the total number of necessary lane changes and the traffic flow rate. This information is used to define the Service Area. Note that, the traffic flow rate determines the possibility to perform lane changes. The Service Area will be larger if a high number of lane changes is expected. The following timeline describes the specific actions to be taken to deploy Service 3 in the scenario depicted in Fig. 7.

TIMELINE OF SERVICE 3

```
Collect information about traffic stream
Calculate traffic flow rate
Calculate traffic stream composition
Define Service Area
Define traffic separation measures
// Outer lanes for automated vehicles
// Inner lanes for non-automated vehicles
// Instruct vehicles to keep a constant speed
Disseminate traffic separation measures
For each automated vehicle do
  If lane change needed then
    Estimate gap for merging
    If gap large enough then
      Initiate lane change
    Else
      If there are CAVs nearby then
        Initiate cooperative lane change
      Else
        If end of Service Area reached then
          Advise vehicle to trigger a ToC
          Keep driving in the same lane
        Else
          Keep driving in the same lane
          Return 12
        End if
      End if
    End if
  End if
  If end of Service Area reached then
    Resume normal automated driving
  Else
    Keep driving on the same lane
    Return to 29
  End if
End for
For each non-automated vehicle do
  If lane change needed then
    Estimate gap for merging
    If gap large enough then
      Initiate lane change
    Else
      Keep driving on the same lane
      Return 38
    End if
  End if
  If end of Service Area reached then
    Resume normal manual driving
  Else
    Keep driving on the same lane
    Return to 46
  End if
End for
```

D. *Service 4: Manage ToC/MRM by guidance to safe spot*

In complex traffic situations where a ToC cannot be avoided, CAVs might need to execute a MRM if the ToC fails. In most cases, this will imply stopping in the ego-lane which negatively influences the traffic flow and safety. This is especially the case inside areas of high complexity or high speed, like motorways. To reduce these negative effects, Service 4 provides a set of safe spots where it is possible to perform the MRM. CAVs will use this information to perform the MRM reducing their impact in the traffic flow and safety.

Fig. 8 shows a scenario where Service 4 can be used. This scenario considers a road works area covering one lane of a two-lane motorway. Some CAVs may not be able to pass the road works area without any additional guidance, for example, due to missing lane markings. Therefore, it will be necessary to trigger a ToC. If the ToC is not successful, the CAV will need to execute a MRM. To avoid the negative impact of a MRM in the free lane, the infrastructure will define a safe spot in front of the road works area and disseminate it to the upcoming CAVs. Service 4 can be applied to multiple different scenarios and to multiple different kinds of safe spots (i.e. emergency lanes, safe heavens, parking areas, etc.). It can be considered as an additional measure for the other services defined, that would be used when any ToC is about to fail and the impact of MRMs should be reduced.

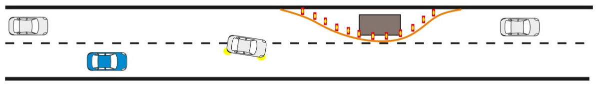

Fig. 8. Scenario where Service 4 can be applied [9]

The following timeline describes the sequence of actions needed to apply Service 4 in the scenario depicted in Fig. 8.

TIMELINE OF SERVICE 4

```
Collect information about the area
Collect information about the traffic
Define Service Area
Identify the safe spots
Determine status of safe spots
Alert vehicles about the road works
While no free safe spots do
  Monitor safe spots
End while
Disseminate free safe spots
For each CAV do
  If ToC needed then
    Reserve safe spot
    Infrastructure computes speed and lane
     advices for surrounding connected vehicles
    Infrastructure disseminates advices
    If ToC fails then
      Initiate MRM
      Move to safe spot
      All surrounding vehicles follow advices
      Acquire target speed
      If lane change needed then
        Estimate gap for merging
        If gap large enough then
          Initiate lane change
        Else
          If there are CAVs nearby then
            Initiate cooperative lane change
          Else
            Return 29
          End if
        End if
      End if
      CAV ends the MRM at the safe spot
    End if
  End if
End for
```

E. *Service 5: Distribute ToC/MRM by scheduling ToC*

Transitions of control can disturb the traffic flow and safety at Transition Areas where multiple ToCs might occur. To prevent these negative effects in mixed traffic scenarios, a distribute ToC solution is applied in Service 5. ToCs are distributed in time and space upstream of the Transition Area. As a result, the ToCs are extended to a large area and thus the negative effects of ToC in the traffic flow and safety are reduced.

Fig. 9 shows a scenario where Service 5 could be applied. This scenario considers that multiple CAVs are approaching an area where the automated driving is not possible. This can occur because the automated driving mode reaches its system limits, due to the complexity of the situation, or due to a particular traffic regulation that forbids the automated mode at this area. The infrastructure will collect information about the upcoming traffic and distribute the ToCs in time and space on the road, reducing the negative impacts of multiple transitions in the same area. Note that this service can be applied to any possible scenario where the transitions of control are predictable, but not preventable.

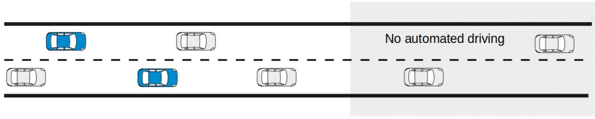

Fig. 9. Scenario where Service 5 can be applied [9]

In Service 5, it is also necessary to collect information about the traffic stream composition to know which of the upcoming vehicles need to perform a ToC. Furthermore, it is also necessary to define additional safety measures for the vehicles next to each CAV performing a ToC. This can be needed to facilitate the execution of a safe ToC (i.e. increase the distance separation with the CAV). CAVs entering the Service Area are stored in a virtual queue. This virtual queue is used to establish the order of execution of the ToCs. The following timeline describes the sequence of needed to deploy Service 5 in the scenario depicted in Fig. 9.

TIMELINE OF SERVICE 5

```
1.  Collect information about the area
2.  Collect information about traffic stream
3.  Calculate traffic stream composition
4.  Define Service Area
5.  Alert vehicles about the no AD-zone
6.  Create virtual queue for CAVs
7.  Decide the places for executing ToC
8.  For each CAV entering in the area do
9.    Determine CAV rank in the virtual queue
10.   Add CAV to virtual queue
11.   Select the next CAVs to execute ToC
12.   For each selected CAV do
13.     Disseminate time and place of the ToC
14.     Instruct nearby CAVs with safety measures
15.     CAV executes ToC
16.     Nearby CAVs execute safety measures
17.   End for
18.   Check for CAVs that leaved the area or
      performed a ToC
19.   Remove those CAVs from the virtual queue
20. End for
```

V. CONCLUSIONS

This paper presents the first set of cooperative traffic management measures to minimize the negative effect of transitions of control in Transition Areas. Different measures have been defined for different scenarios and mixed traffic conditions where automated, connected and conventional vehicles coexist.

The management of transitions of control at Transition Areas is an open research topic that needs to be further investigated. The TransAID project has identified the open challenges that need to be addressed to avoid potential dangerous situations that multiple transitions of control can produce if they are not properly managed. For example, limited work has been done on the design of realistic models of the behavior of vehicles and human drivers during a ToC. From a C-ITS point of view, it needs to be investigated if the available standard V2X messages can be accordingly profiled to support the above mentioned measures, or if extensions are needed. For example, the ETSI technical Committee on ITS is currently defining the so called CPM (Collective Perception Message), but appropriate triggering conditions will be needed to avoid overloading the radio channel while ensuring the timely reception of information. New cooperative driving mechanisms will also be needed for the efficient and safe coordination of driving maneuvers. To this aim, ETSI TC ITS is also defining the MCM (Maneuver Coordination Message), which is expected to include information about each vehicle's planned maneuvers. This work and future research in cooperative management of ToCs could serve as an input for the standardization bodies. Finally, continuous efforts will be needed to identify other relevant Transition Areas and the corresponding traffic management measures, since limited information is available about the actual performance of automated vehicles in Transition Areas.

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