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Infrastructure for the Extension of ODDs – applied in connected and aUtomated driving and Standardization procedures

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***Abstract*—This paper introduces the iEXODDUS project, which aims to enhance the infrastructure supporting automated vehicles to manage the complexities of their environments. The project is advancing digital technologies and navigation services to improve safety, security, and sustainability in the mobility sector, thus paving the way for more reliable automated transportation. iEXODDUS will meticulously assess existing Operational Design Domains (ODDs) to identify limitations and areas for improvement, fostering a comprehensive understanding of ODD challenges and opportunities. This analysis will form the foundation for a framework to assess and categorize ODDs across various automated driving scenarios. A key focus is on enhancing sensor technologies and perception capabilities through advanced data fusion methods, expanding ODDs beyond current limits while considering environmental factors such as weather conditions and road infrastructure. The project envisions autonomous vehicles travelling across Europe, addressing harmonization and legal issues, and making policy recommendations. Collaboration with industry stakeholders and real-world demonstrations will enable an industry-tailored approach to automated driving systems with extended ODDs. iEXODDUS aims to significantly improve ODDs for typical automated driving functions, ensuring continuous driving automation on European motorways through a combination of in-vehicle and infrastructure-based solutions. The project will address specific ODD challenges in roadwork zones, tunnels, urban canyons, and road incident sites to ensure safe, secure, and efficient automated driving operations.**

I. Introduction

Europe must manage the transition towards safe, resilient, and sustainable transportation systems, alongside demand-driven, smart mobility services [1]. By reducing accidents caused by human error, minimizing traffic congestion, lowering energy consumption, and cutting vehicle emissions, while simultaneously increasing the efficiency and productivity of transporting people and goods, research and innovation are expected to generate substantial safety, environmental, economic, and social benefits.

For this transformation to succeed, Europe's transportation infrastructure must be equipped to support cleaner and smarter mobility. In parallel, it is essential for Europe to maintain a high standard of transportation safety for its citizens. Developing resilience within transportation networks—allowing them to prevent, withstand, and recover from disruptions—is also critical. This transformation will rely on a strong foundation of research and innovation across technology, legislation, and human factors.

II. State of the Art

Automated driving has significant promise in meeting Europe's requirement for safe, resilient and sustainable transportation [2]. Autonomous vehicles can drastically reduce accidents caused by human error, a key contributor to road accidents, by harnessing cutting-edge technologies. They have the ability to improve European residents' transportation safety and make roadways more secure.

Transportation has experienced a paradigm shift with the rapid development of various levels of autonomous vehicle technology, which promises improvements in both efficiency and safety. However, the operational capability of these autonomous vehicles remains constrained by unresolved issues and limitations in system components such as sensing and perception [3], behavior prediction, and reliability [4]. These challenges impose significant restrictions on their Operational Design Domains (ODDs) [5].

To ensure safety, all driving functions must operate within clearly defined limits. Three key driving function types—Valet Parking, City Shuttles, and Motorway Chauffeur—are currently gaining traction, each setting constraints on a specific parameter of the ODD. The ODD, initially defined in [6] and further standardized in [7], serves as a framework for specifying the conditions under which an automated vehicle can safely operate.

Driving functions designed for more complex environments (e.g., valet parking and city shuttles) typically face stricter limitations on operational speed. In contrast, functions with lower complexity in terms of dynamic objects and road network (e.g., motorway chauffeur) allow for higher speeds. Regulations governing homologation have been established for all driving functions, such as [8], which outlines the certification process for Automated Lane-Keeping Systems (ALKS).

Various factors, such as weather conditions, road types, traffic patterns, and speed restrictions, must be considered to

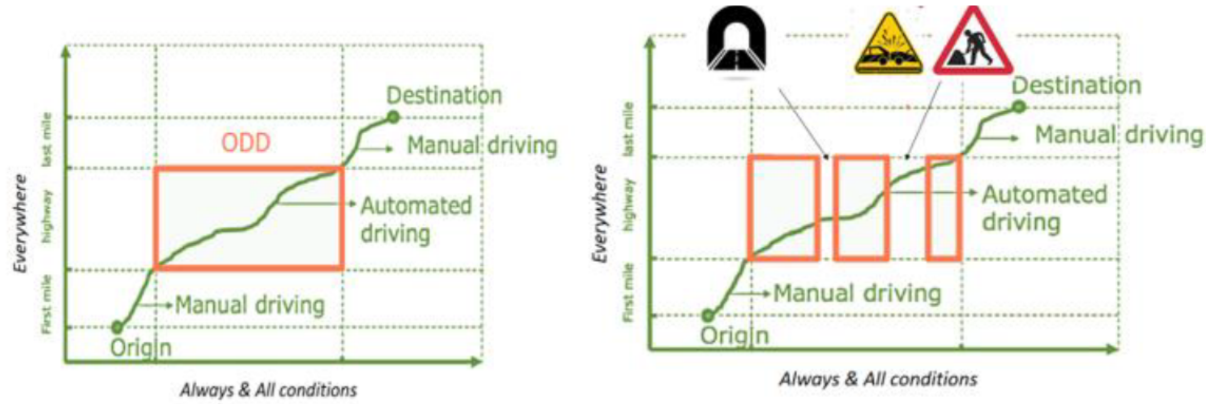

Fig. 1. Highway ODD and ODD interruptions baed on [9].

ensure the safe operation of autonomous vehicles. A well-defined ODD is crucial for safe functioning, and any extension of the ODD must be accompanied by enhancements in the capabilities of the automated driving function. These extensions must also address all safety concerns arising from the broader range of applicable scenarios.

Figure 1 illustrates ODD interruptions for an Automated Lane-Keeping System (ALKS) on the motorway. The first and last mile of a journey, due to limitations in the ALKS system, still requires manual driving by the human driver. Once the vehicle enters the motorway, the ALKS system takes over the operation, theoretically continuing until the vehicle exits the motorway. However, in practice, events such as accidents, roadwork zones, or specific infrastructure challenges like tunnels often necessitate a handover back to the driver.

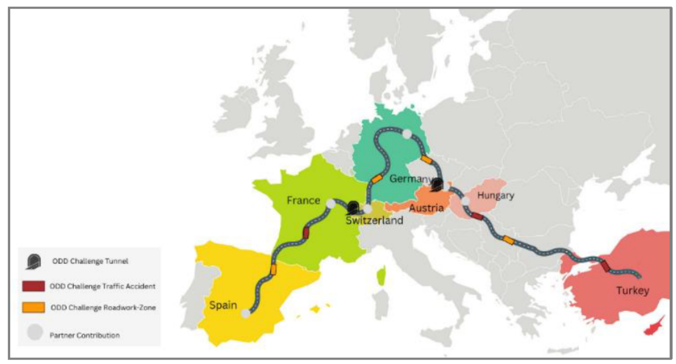

Fig. 2. iEXODDUS Vision illustrated with a hypothetical drive through Europe.

III. Vision and Targets

During the course of iEXODDUS, the consortium aims to extend the ODD to enable automated vehicles to navigate challenging scenarios such as construction zones, unmarked roads, and ambiguous traffic situations. By expanding the ODD, vehicles can better handle unexpected situations, reducing the likelihood of accidents and improving overall safety. The ODD extension also allows automated vehicles to operate in diverse weather conditions, including heavy rain, snow, and fog. Incorporating robust perception and decision-making algorithms enables vehicles to effectively respond to environmental challenges, thereby mitigating potential risks. Furthermore, the proposed ODD extension allows automated vehicles to adapt to changes in road infrastructure, such as new traffic signs, lane markings, and construction zones. Vehicle navigation through evolving road environments is improved by updating their perception models and decision-making algorithms with external data from infrastructure and other road users.

Extending the ODD reduces the number of situations where drivers must take over control when approaching the ODD limits. Minimizing handover scenarios leads to smoother and more efficient operations while reducing the potential for human errors during critical situations. Additionally, expanding the ODD facilitates better integration between automated and human-driven vehicles, thus increasing the penetration rate of automated vehicles. By enhancing the effectiveness of prediction and human driver/VRU behavior recognition, traffic flow and safety will be improved, facilitating automated vehicle operation in a wider range of scenarios. However, several challenges are associated with extending ODDs, including the need for comprehensive data collection, robust sensor technologies, advanced perception algorithms, and regulatory frameworks that support expanded ODDs. These challenges require interdisciplinary collaborations and continuous advancements in technology and policymaking.

There is immense potential to enhance safety and robustness in autonomous transportation by extending the ODDs of automated vehicles. By enabling vehicles to operate in more diverse scenarios and adapt to changing environments, the extension of ODDs paves the way for safer, more reliable, and seamlessly integrated automated vehicles on our roads. Figure 2 illustrates the ultimate goal of seamless integration: a trip of an automated vehicle from Turkey to Spain via several European partner countries.

The iEXODDUS project is strategically positioned to achieve the High-Level Goals of Cluster 5 and Destination 6 by spearheading the development of critical digital technologies and advanced navigation services [1]. Aligned with these goals, iEXODDUS will drive accelerated transformations in the mobility sector, enhancing safety, security, and sustainability.

The iEXODDUS consortium aims to address current limitations and demonstrate its solutions across various European countries, showcasing extended ODDs through specific use cases. The project objectives are as follows:

- **Objective-1:** Develop and demonstrate solutions that leverage infrastructure and advanced onboard systems to enhance the continuity and expansion of ODDs for connected automated vehicles.
- **Objective-2:** Analyze and create feasible systems, data, and service architectures for Digital Twins for road transport infrastructure.
- **Objective-3:** Achieve future-proof and extendable CCAM services by fostering advanced and functionally safe collaboration between CCAM actors for the sake of ODD continuity and extension.
- **Objective-4:** Contribute to the standardization of vehicle- and infrastructure-side technologies and develop business and governance models (including organizational procedures and the right-to-use data) for digital twins, addressing legal, trust, and data security topics.
- **Objective-5:** Develop specific real-life use case demonstrations of infrastructure-assisted extended ODD functionalities, potentially including mixed (automated and manual) traffic elements.

In conclusion, the outlined objectives aim to advance connected automated vehicle technologies by focusing on key areas such as extending ODDs through infrastructure and advanced systems, developing digital twin architectures for road transport, and ensuring future-proof, collaborative CCAM services. Additionally, these objectives emphasize the importance of contributing to the standardization of vehicle and infrastructure technologies, alongside addressing legal, trust, and data security concerns through appropriate business and governance models. Finally, the practical demonstration of these advancements in real-life use cases, including mixed traffic environments, will further showcase the potential of infrastructure-assisted ODD functionalities.

IV. Specific iEXODDUS Use-Cases

The rapid development of autonomous vehicle technology has ushered in a paradigm shift in transportation, promising increased efficiency and safety. However, the operational capabilities of these vehicles remain limited by the constraints of existing ODDs. ODDs define the specific conditions under which an automated vehicle can safely operate, factoring in elements such as weather conditions, road types, traffic patterns, and speed limits. Establishing and adhering to a clear ODD is essential for ensuring the safe operation of autonomous vehicles, highlighting the need to expand ODDs to address safety challenges and enhance vehicle resilience.

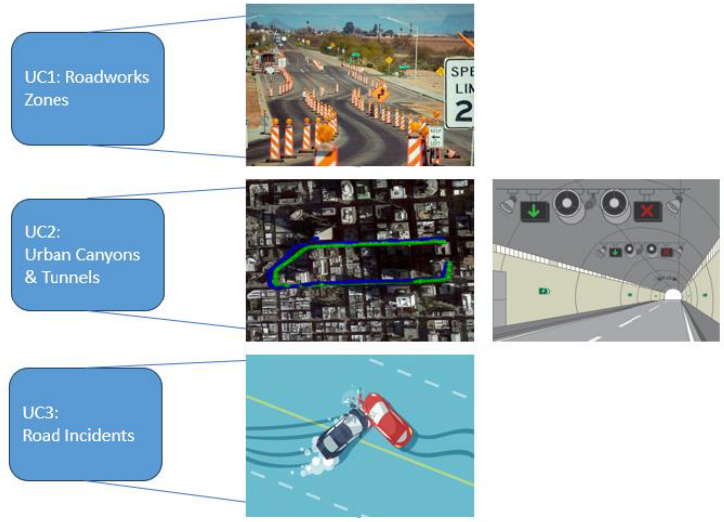

Fig. 3. iEXODDUS Project main use-cases.

Expanding ODDs allows autonomous vehicles to navigate more complex scenarios, such as construction zones, unmarked roads, and ambiguous traffic situations, improving their ability to handle unexpected events. This reduces the likelihood of accidents and significantly enhances overall safety. Furthermore, an extended ODD enables these vehicles to function in a wider range of weather conditions, including heavy rain, snow, and fog. By integrating advanced perception and decision-making algorithms, vehicles can respond effectively to environmental challenges, mitigating risks and ensuring safer, more reliable autonomous transportation.

The following use cases illustrated in Figure 3, which will be developed as part of the iEXODDUS project, aim to demonstrate how extended ODD functionalities can be applied in real-world scenarios. These future implementations will provide valuable insights into how autonomous vehicles can operate safely and efficiently in diverse and challenging conditions, highlighting the potential of infrastructure-assisted technologies to support broader ODD applications.

A. Use Case-1 (UC1): Navigate through Urban Canyons and Tunnels for CCAM Actors

1) Description: Current Level-3 autonomous vehicles require a driver handover when passing through tunnel sections, as GNSS-based localization becomes non-functional. To address this limitation, there is a pressing need for ODD extensions that enable automated driving in GNSS-denied environments.

2) Initial Situation: Tunnels present a significant challenge for the continuity of the ODD, as GNSS signals degrade, and the confined tunnel walls create difficulties for perception sensors.

3) Goal: Ensuring reliable localization in GNSS-denied environments and enabling a seamless transition between GNSS-based and non-GNSS-based localization modes are critical for safe autonomous vehicle operation.

4) Method: Various countermeasures will be explored and compared, ranging from providing tunnel details via C-ITS to fusing data from other in-vehicle sensors (such as tire rotation), odometry and inertial sensors. Additionally, the installation of UWB tags in both the tunnel and the vehicle will be considered.

5) KPIs: Successful simulation development and subsequent on-road demonstrations that validate the ability of autonomous vehicles to operate safely and efficiently under real-world conditions, including challenging environments such as tunnel sections.

6) Impact: Extended ODD for Level 3 and 4 vehicles, enabling seamless operation through tunnel sections.

B. Use Case-2 (UC2): Navigate through Road works zones for CCAM Actors

1) Description: Work zones present a significant challenge for autonomous vehicles, particularly in terms of perception and decision-making. Current sensor capabilities are insufficient for accurately detecting and interpreting work zone setups in advance.

2) Initial Situation: Autonomous vehicles can manage decision-making challenges at low speeds; however, effective handling of work zones requires cooperative traffic flow management and over-the-air updates to HD maps in advance.

3) Goal: Enable autonomous vehicles to navigate work zones safely while ensuring the communication of critical information to other road users.

4) Method: Roadside units (RSUs) can serve as the foundation for accurately measuring work zone dimensions. This information should be stored in a centralized management system. Additionally, connectivity through V2I (Vehicle-to-Infrastructure) is necessary, while V2V (Vehicle-to-Vehicle) communication should be explored, though it may not be essential in the initial stages.

5) KPIs: Achieve a 25% reduction in control transitions from the vehicle to the driver in a defined set of driving scenarios, enhancing the continuity of autonomous vehicle operations and minimizing the need for human intervention.

6) Impact: UC2 is likely to significantly improve the ability of connected and automated vehicles to safely and efficiently navigate complex work zones, reducing delays and increasing safety for both autonomous vehicles and other road users.

C. Use Case-3 (UC3): Navigate through incident zones for CCAM Actors

1) Description: Navigate Through Incident Zones for CCAM Actors" use case aims to enhance the ability of automated vehicles to safely and efficiently respond to unpredictable situations such as accidents and road closures. By leveraging V2I, V2V communication, and real-time updates to HD maps, CCAM vehicles will navigate incident zones with minimal driver intervention, improving safety and reducing traffic disruptions.

2) Initial Situation: Currently, autonomous vehicles and CCAM systems face significant challenges when navigating through incident zones, such as accidents, breakdowns, or emergency response areas. These scenarios often involve unpredictable changes in traffic patterns, temporary lane closures, and the presence of emergency personnel, requiring quick and complex decision-making. Existing sensor technologies and perception systems struggle to fully detect and respond to these dynamic environments, leading to a reliance on human intervention. Furthermore, communication between vehicles and infrastructure is limited, preventing the timely exchange of critical information needed to ensure safe and efficient navigation through such zones.

3) Goal: Collect, aggregate, and distribute essential information regarding the Pre-Incident, Warning, and Incident Areas to ensure that autonomous vehicles can respond effectively and safely to dynamic road conditions.

4) Method: Prepare autonomous vehicles for navigating through incident areas by localizing the incident, evaluating the number of affected lanes, and identifying the type of disruption (e.g., accident, adverse weather, or object on the road). This information will enable vehicles to adjust their route and behavior accordingly, ensuring safe and efficient passage through the affected zone.

5) KPIs: Achieve a 35% increase in traffic flow in predefined incident or accident scenarios through enhanced autonomous vehicle navigation and real-time information sharing.

6) Impact: Extend the ODD for Level 3+ vehicles to enable seamless operation in incident sites, allowing autonomous vehicles to navigate safely and efficiently through complex and dynamic environments.

V. Underlying Architecture-related innovations of the iEXODDUS Project

The iEXODDUS project introduces key architectural innovations aimed at extending the ODDs for connected and automated vehicle operations. These innovations, illustrated in Figure 4, focus on creating a robust and scalable system that integrates real-time data, advanced digital twins, and vehicle-to-infrastructure communication. By extending the ODD to cover complex environments such as highway construction sites and incident zones, the project seeks to enhance the safety, efficiency, and functionality of automated driving, ensuring seamless vehicle operation even in challenging conditions.

A. iEXODDUS System Requirements:

The iEXODDUS project aims to develop an advanced system capable of addressing several critical challenges in connected and automated mobility. First, it should ensure accurate detection of work zone settings using technologies such as camera-based detection, Lidar-based detection, and communication-based detection. This information must be effectively communicated to all road users to enhance safety.

Additionally, the system should provide real-time speed limitation guidance and meaningful traffic jam advice in areas surrounding traffic incidents, work zones, or regions with reduced GNSS signals. This includes managing traffic flow through methods like speed harmonization, shock wave damping, or cooperative actions among connected and autonomous vehicles (CAVs), such as assisted lane changes.

Another key requirement is to ensure reliable localization in GNSS-denied environments, with smooth transitions between GNSS-based and non-GNSS-based localization modes. To further improve safety and reduce emissions, iEXODDUS must offer systems capable of guiding vehicles with suggested speeds and early warnings, while maintaining smart gaps between vehicles to optimize traffic flow.

Work zone personnel also require protection, and iEXODDUS must provide a system to track and warn road workers, preventing harm to vulnerable road users (VRUs) such as motorcyclists and workers present in work zones, even on highways closed to pedestrians and bikers. Moreover, the system should accurately localize incidents, identify affected lanes, and detect any objects or obstacles on the road during the transition phase.

During incidents, the system must detect and communicate the presence of other hazards, such as rockfalls, spilled cargo, or oil spills. After the incident or work zone, iEXODDUS should recommend the appropriate lane for vehicles and adjust speed limitations accordingly.

Furthermore, iEXODDUS will incorporate a communication framework that standardizes the transmission of work zone settings and real-time HD map updates to vehicles. The system will maintain a digital twin by integrating inputs from multiple sources and harmonizing data across the EU, including standardized communication of road conditions and real-time updates to HD maps and digital twins.

Lastly, iEXODDUS should feature a warning system capable of predicting potential crashes by analyzing data from both infrastructure and vehicles, enhancing safety through proactive measures.

B. Analysis Aspects of iEXODDUS:

The use cases within the iEXODDUS project will be analyzed from several key aspects, with a primary focus on enabling the continuity and extension of the ODD. This analysis will explore how the proposed solutions ensure safe and seamless operation of connected and automated vehicles in diverse and challenging scenarios, including work zones, incident areas, and GNSS-denied environments.

The iEXODDUS project will conduct a comprehensive analysis of highway road work zones across several European countries. This will involve developing a standardized categorization scheme to assess the complexity of these zones in relation to the operational capabilities of automated vehicles. The project will also analyze critical situations, conflicts, and accidents that occur on highways, providing valuable insights for improving safety.

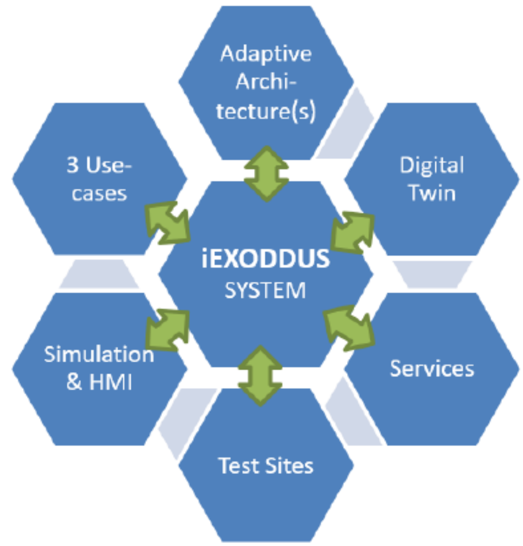

Fig. 4. iEXODDUS System and innovations.

A key focus will be the conceptualization of a highly automated driving function tailored for construction sites of selected categories. This will emphasize high-precision localization, including redundancy measures, free space detection, and the development of both on-board and off-board environmental models. Based on the categorization of construction sites, a prototypical driving strategy will be developed. For example, strategies may include staying in lanes with emergency stopping potential or avoiding lanes with insufficient separation from oncoming traffic.

The project will also enhance the protection of road workers by improving worker tracking through infrastructure-based systems, which will then be integrated into the Digital Twin. These advancements will benefit vehicles equipped with L0-L2 technology as well. Furthermore, data acquisition and the virtual modelling of human driver behavior in construction sites will be used to inform the Digital Twin and validate automated driving functions.

Additionally, the project will build, use, and present experimental vehicles to demonstrate these advancements in real-world scenarios.

C. Virtual development and digital twins in iEXODDUS:

A key goal of the iEXODDUS project is to create Digital Twins for critical highway environments, including construction sites, tunnels, and incident areas. These virtual representations will allow for real-time updates and enhanced safety for autonomous vehicle operations.

The project will develop Digital Twins of construction sites, starting with a virtual representation before the site is installed and continuously updating as the site evolves. All vehicles will act as cloud-based sensors, leveraging technologies such as SLAM (Simultaneous Localization and Mapping) and GNSS, to provide real-time, standardized information about the site.

Additionally, the Digital Twin will encompass a comprehensive virtual model of the vehicle itself, including its localization, backend systems, environmental models (both on-board and off-board), and its driving strategy. This model will also include Level 3 autonomous functions, and could eventually integrate into larger data-sharing ecosystems like GAIA-X, utilizing inputs from road authorities and operators.

The project will use virtual simulations to validate automated driving functions, employing the Digital Twin for prospective safety assessments. These simulations will also be used to upgrade and test the Digital Twin to support homologation and standardized validation processes before market release.

D. Standardization Goals of iEXODDUS:

The iEXODDUS project aims to contribute to European standardization efforts by establishing guidelines and frameworks for the implementation of Digital Twins and automated vehicle functions. This includes defining the basic layout and properties of Digital Twins, with particular focus on trust, data security, and governance models.

Additionally, the project will provide recommendations for the design, safety features, and continuous monitoring of highway construction sites. These recommendations will leverage vehicles as cloud-based sensors, feeding real-time data into the Digital Twin to ensure accurate and up-to-date representations.

Finally, the project will offer guidance on the design, homologation, and validation of Level 3 autonomous highway driving functions, specifically in the context of navigating highway construction zones.

VI. Conclusion

Within this paper, the novel European project iEXODDUS presented. Currently available driving functions are challenged and tbe bounderies for existing Highway-ODDs are going to be extended through improved technologies (improved perception, enhanced and robust localisation, robustness against adverse weather) and infrastructure support measures like data provided by infrastructure services.

The overall expected technical impact of iEXODDUS is depicted on Figure 5. By realising the three proposed technical use-cases a continuity of the ODD shall be achieved, Europe's path towards a more digital economy is supported and safety for a mixed traffic system is increased.

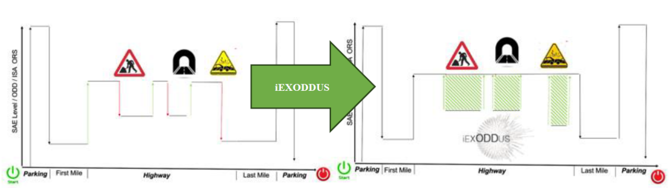

Fig. 5. ODD extension concept by iEXODDUS

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