StreetWise

SCENARIO-BASED SAFETY VALIDATION OF CONNECTED AND AUTOMATED DRIVING

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DATE
July 2018

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Contents

1 CHALLENGES IN TESTING AUTOMATED DRIVING SYSTEMS

Automated Driving (AD) technology is anticipated to be a key aspect for achieving a higher level of road safety, a further reduction of harmful emissions, improving traffic flow, increasing comfort and ensuring mobility for all, including elderly and impaired. As AD technology is rapidly being developed, an increasing number of driving tasks in vehicles is currently being taken over by automation in Advanced Driver Assistance Systems (ADAS). With the transition towards Connected and Automated Driving (CAD), automation is expected to further increase until the driver is completely out of the driving loop [1]. An important aspect in this continuous development is the safety assessment of the road worthiness of these new functions and systems.

Intensive testing and assessment of automotive technology to ensure implementation of new safety and comfort systems and functionalities has become state of the art in the last decades. Safety driven assessments such as Euro NCAP have promoted the implementation of new functions and strongly enhanced the overall car safety performance, both to prevent accidents and to mitigate the possible consequences.

Currently the performance of new systems is assessed in case-by-case situations i.e. for single use cases. For example, an autonomous emergency braking (AEB) system is tested in critical car-to-car situations that would result in an accident if no system response is issued. However, as AD systems become more and more automated and integrated, their operational design domain (ODD) becomes increasingly large, complex and dynamic. Therefore, case-by-case testing of individual functions is no longer sufficient to ensure operational safety on the road (more on automotive safety concepts in the blue text block).

One way to overcome the limitations of case-by-case testing is test-driving with automated vehicle prototypes on public roads. This is an expensive and time consuming alternative. Millions and possibly billions of driving kilometres may be needed to get sufficient ‘driving events’ to expose the AD functionality under test and to provide evidence of performance according to safety requirements. According to Bosch, even for high technology readiness level functionalities such as a highway pilot, several million kilometres of test-driving need to be completed before the function can be released for production [2]. Following a more theoretical approach by applying the ISO 26262 ASIL D [3], it is found that easily over 200 million test driving

kilometres are needed for validation of automated diving functionalities.
Maurer and Stiller comment that: “If testing and assessment methods cannot keep pace with this functional growth, they will become the bottleneck of the introduction of ADAS to the market.’’ [4]

Therefore, the development of efficient validation and testing methods is essential to pave the way for automated driving.

Automotive Safety

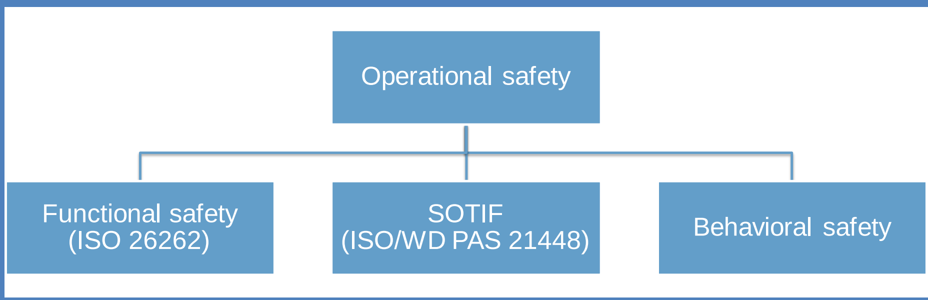

Figure 1: Automotive safety aspects

Operational safety has the goal to minimise the occurrence and consequences of traffic accidents. This entails both passive and active safety technologies. An example is the Euro NCAP test protocol for Autonomous Emergency Braking systems [6]. Operational safety can be broken down into three main aspects, as shown in Figure 1: Functional Safety, Safety of the Intended Functionality (SOTIF) [5], and Behavioural Safety.

The functional safety of electrical and/or electronic systems in production automobiles is ensured by the international standard ISO 26262 [3]. This standard forms an integral part of the automotive product development phase to ensure the individual function works as expected. Functional safety is concentrating on system design mitigating consequences of malfunctions that may occur in the components of the automated system.

For safety of ADAS and CAD it is important to take into account the perception of the system and its decision making. These aspects are considered in SOTIF. The objective of SOTIF is to validate the automated function in all relevant environmental scenarios, especially in difficult conditions for both sensors and algorithms.

The third aspect in operational safety is behavioural safety. Its focus is on system design to behave safely in its environment to avoid hazards and reduce the risk of mishaps.

2 SCENARIO BASED APPROACH

Test drives with prototype driving systems appear to be an enormous effort. It does not seem to be feasible to drive these millions of kilometres with the increased speed of development of automated driving functions and the high level of safety requirements that are expected from these functions. Moreover, most of the events occurring during these test drives are rather common, while other events might only occur once in several million of kilometres. Therefore there is an essential need for constructing and collecting relevant traffic events and situations (scenarios) for testing and validation of AD functionalities. The collection of these scenarios should in principal represent and cover the entire range of real-world traffic situations that might be encountered by the AD system under test.

In this paper TNO presents StreetWise, a newly developed methodology for building and maintaining a real-world scenario database, suitable for testing and validation of automated driving functions. The underlying scenarios are extracted from real-world microscopic traffic data, i.e. data collected on the level of individual vehicles.

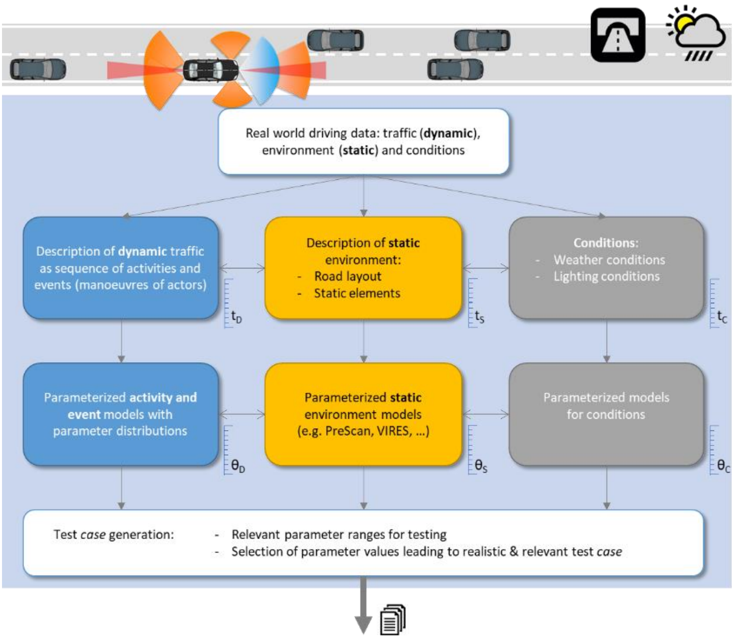

Figure 2: Test case generation using real-world scenarios

These scenarios are called ‘real-world scenarios’. Typically they include e.g. road layout, subjects involved, manoeuvres, relative distances, speeds, view blocking obstructions, weather and light conditions.

The StreetWise database is continuously extended by monitoring the situations that vehicles encounter on the road and distinguishing between different scenarios. Gradually, with analysing a large number of kilometres and hours of data, this collection of scenarios will be more and more representative for the situations that a car may encounter when deployed on public roads in a certain geographical area. The database stores the collected scenarios efficiently and allows for fast search of the appropriate scenarios for testing specific AD functions. Figure 2 sketches how test cases are generated from real-world scenarios.

There are considerable challenges for creating a database of real-world scenarios:

- The amount of Big Data that needs to be processed requires automated mining and classification of scenarios. In addition, storage requirements ask for a significant data reduction since an automated vehicle may easily produce many terabytes per hour. The scenario database should allow for a fast search based on the sensors and functionality that the system under test is equipped with.
- The scenario database needs to be representative of the real world, and should be able to describe the relevant scenarios that may happen on the road. It is therefore important to give a measure of completeness of the database: a metric that indicates how many of all possible scenarios the database contains.
- In addition, testing requires that a limited set of test cases can be generated from a set of representative real-world scenarios in the database. A selection procedure should result in a reasonable number of relevant test cases that cover the full operational range of the system-under-test. A fair, relevant and realistic assessment and test matrix needs to be set up, providing an indication which of the test cases are required to be tested physically, and for which tests, virtual simulations suffice.

Scenario-based safety validation of automated driving is broadly supported by the automotive community. This is reflected in a draft standard of NHTSA and the ISO 26262 working group on SOTIF. Related projects in Germany (Pegasus [7]) and EU (ENABLE-S3 [8]) strongly support this approach.

This vision paper gives a detailed description of the StreetWise methodology developed by TNO. The methodology provides a solution on how to create such a scenario database from real-world data and how to use it in the assessment of automated driving functions. A roadmap is provided on how the methodology is designed to evolve with the increasing automation and communication in the road mobility systems.

3 STREETWISE METHOD

StreetWise is a continuous process of mining scenarios out of real-world data collected by a fleet of vehicles in different cities, regions, countries, and continents, and storing these scenarios into a structured database for scenario analysis and test case generation. Herewith the StreetWise scenario database allows for statistical analysis regarding representativeness of scenarios that any vehicle (and its automated systems) might encounter on the road. It provides a reliable source for generation of well-defined and relevant test cases for the assessment of ADAS and AD systems. The user-model allows participants in StreetWise to contribute to the database with data collected from their fleet of test and prototype vehicles. In return, they receive access to all collected scenarios stored in the StreetWise database.

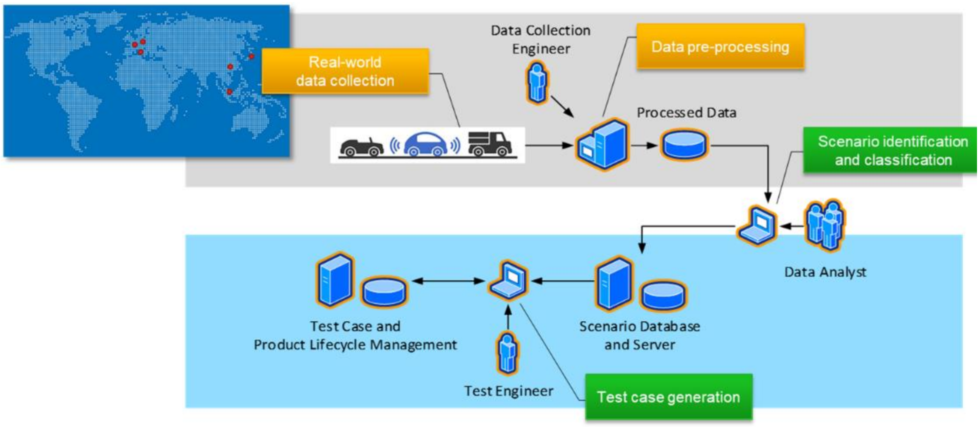

Figure 3: StreetWise pipeline and workflow

The StreetWise pipeline and workflow is schematically outlined in Figure 3. The main steps in the workflow are explained in Table 1:

Workflow	Description
Real world data logging	Data collection using the sensor systems onboard a vehicle. Data is collected at the level of objects. Raw sensor data are not stored or analysed in StreetWise.
Data pre-processing	Object level data is validated and labelled for analysis, e.g. with GPS location, time and date.
Scenario identification and classification	• Scenario identification from real-world data; • Scenario classification and parameterization including the generation of probability density functions (PDF) of the scenario parameters.
Test case generation	• Studying the occurrence and relevance of scenarios to support the development of ADAS and automated driving systems.

	• Test case generation for virtual simulation and physical testing based on selected scenarios

Table 1: Description of the workflow steps of StreetWise as depicted in Figure 3

Before elaborating on how to extract real-world scenarios and to use them for validating automated driving functions, we introduce our definition for a scenario and its elements of which a scenario is constructed from the perspective of an ego vehicle driving on the road.

3.1 Definitions of scenario and scenario elements

A scenario is a typical manoeuvre on the road with the complete set of relevant conditions and trajectories of other traffic participants that have an interaction with the ego vehicle over a relevant time period, typically in the order of seconds. A ride on the road can in this way be described by a continuous sequence of scenarios, where scenarios might overlap in time. In our framework we define a traffic scenario such that it is consistent with existing definitions [12], [13], [14], [15], but sufficiently concrete for scenario mining and scenario based assessment [11].

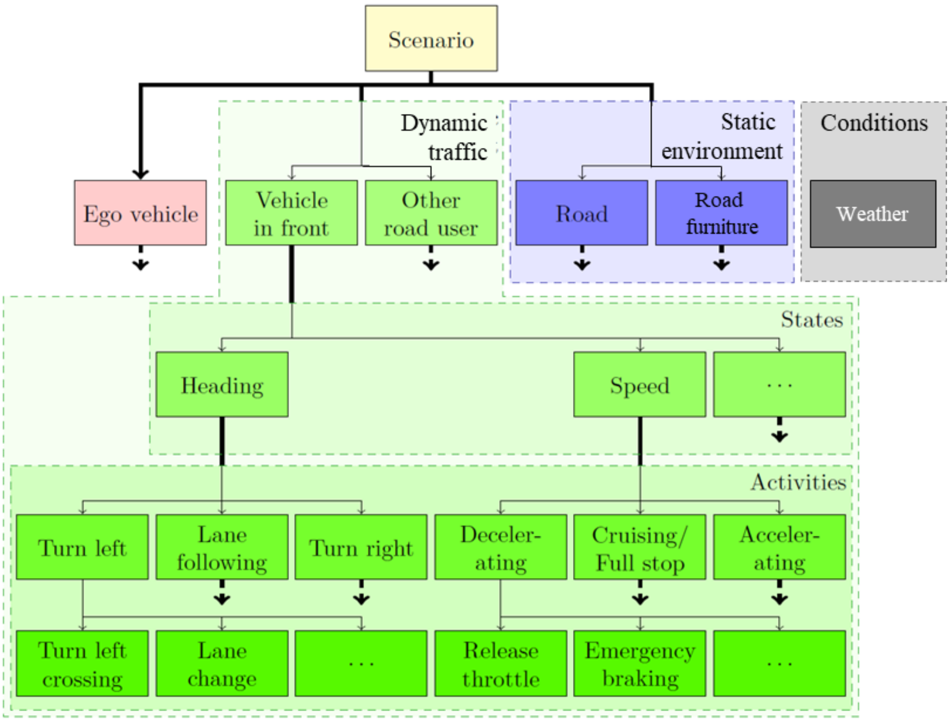

Figure 4: Schematic overview of a scenario.

Figure 4 depicts a schematic overview of a scenario.The scenario consists of several elements: the manoeuvre of the ego vehicle, the dynamic environment (e.g. the manoeuvres of other traffic participants, state of traffic lights, and conditions such as weather and light) and static environment (e.g. the layout of the roads, the presence of obstacles, traffic signs).

Definition: *A scenario is a quantitative description of the ego vehicle, its activities and/or goals, its dynamic environment (consisting of traffic environment and conditions) and its static environment. From the perspective of the ego vehicle, a scenario contains all relevant events.*

An *activity* is considered the smallest building block of the dynamic part of the scenario (manoeuvre of the ego vehicle and the dynamic environment). An activity is a time evolution of state variables such as speed and heading to describe for instance a lane change, or a braking-to-standstill. The end of an activity marks the start of the next activity. The moment in time that marks the beginning or ending of an activity is called *event.*

Definition: *An event marks the time instant at which a transition of state occurs, such that before and after an event, the state corresponds to two different activities.*

To illustrate the definition of *event* and *activity* we consider an exemplary speed profile of a vehicle as shown in Figure 5:

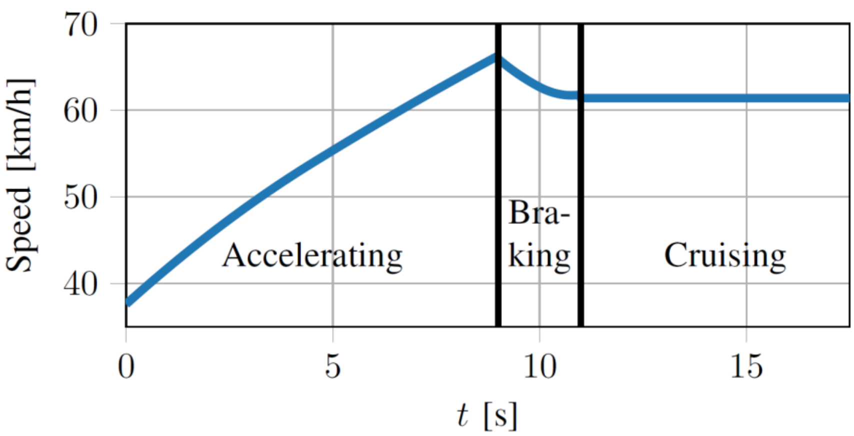

Figure 5: A speed profile of a vehicle showing 3 activities: acceleration, braking and cruising, respectively. The events are indicated by black vertical thick lines.

In the example, two events are identified. At the first event, the longitudinal acceleration changes from being positive to negative, i.e. the vehicle starts braking. The second event marks the time where the acceleration changes from negative to zero, i.e. the vehicle starts cruising. As there are two different events identified, three different activities are to be described namely, ‘accelerating’, ‘braking’, and ‘cruising’, respectively.

> **Definition:** *A scenario class refers to multiple scenarios with a common characteristic. A scenario is an instance of a scenario class*

In literature [16] - [24], many different types of scenarios are considered, such as a cut-in, braking of a predecessor, a near miss, a collision or a safety-critical scenario, an urban scenario, a free-driving or vehicle-following scenario, a lane change, an overtaking action, a platoon merge, an intersection passing, a highway lane reduction, or an urban intersection crossing. In order to get a complete picture of the scenarios that are encountered in traffic, this list of scenarios is further expanded.

Scenario classes are not mutually exclusive, so it may be unclear how a scenario should be classified. For example, a scenario in which a predecessor brakes can be both a braking scenario and an urban scenario. Also, it might be difficult to determine whether the list of scenarios is complete. Moreover, the choice having generic scenario classes – with a high variety or having specific scenario classes – with less variety needs to be balanced.

TNO proposes to adopt tree structures of tags that describe the scenario. A tag can be a label that describes a specific activity of a vehicle, the type of road, or the weather, etc. A combination of tags represents a scenario class.
The tags are structured according to different trees, see Figure 6 to Figure 8 for several examples. Tags that are in the same layer of a branch are mutually exclusive. For example, regarding the weather (Figure 8), it is not possible to have a scenario in which there is clear sky and it is snowing at the same time. The different layers of the trees can be regarded as different abstraction levels [11].

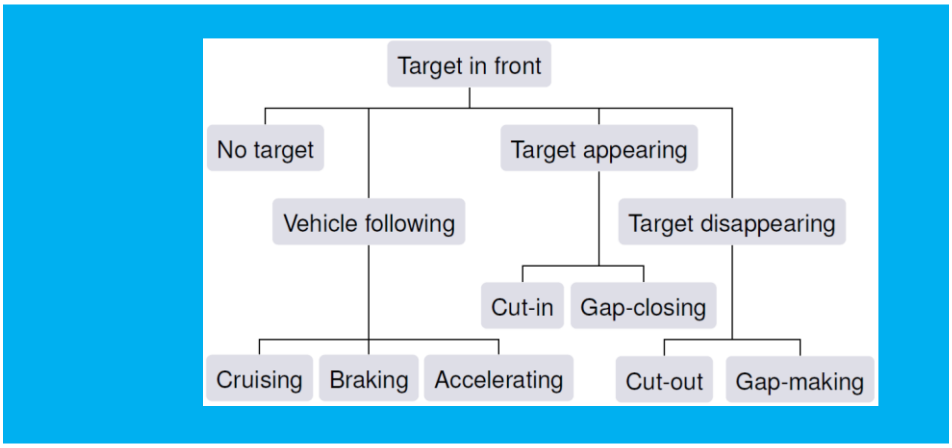

Figure 6: Example of a tree structure for dynamic traffic behaviour

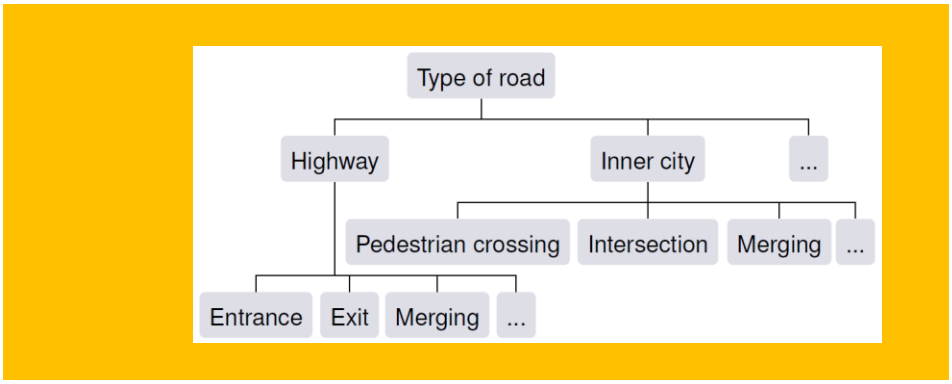

Figure 7: Example of a tree structure for types of road

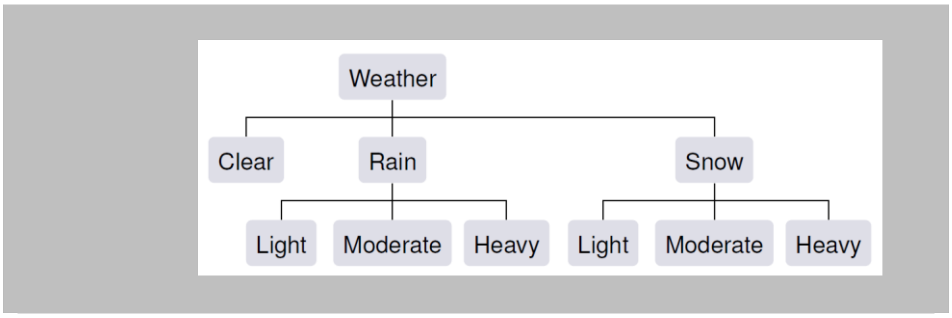

Figure 8: Example of a tree structure for weather conditions

The applied concept of tag trees provides the possibility to define a specific tag that belongs to a more generic tag. For example, when examining the vehicle following behaviour of an automated driving system, one might want to test for all vehicle-following scenarios (see Figure 6), or one can choose to only test for the vehicle-following scenarios with braking involved.

3.2 Data collection

As scenarios describe the *dynamic* manoeuvres of all relevant actors possibly interacting with the ego vehicle the real-world scenario can be generated from the sensors output of the ego vehicle such as accelerometer, camera, radar and Global Positioning System (GPS). This is considered as a minimum set of information that is needed to describe the dynamic part of a scenario. It is possible to extend the contents of a scenario by combining further on-board information from the CAN-bus, such as individual wheel-speeds, braking pressure and steering wheel rotation.

For StreetWise *Object level data* is required, instead of raw sensor data[*]. Object level data, usually the output of sensor fusion algorithms or on-board world modelling tools, provide for all detected objects an ID, a type (e.g. pedestrian, passenger car, truck, motor cycle, general object, etc.), and state variables such as relative position with respect to the ego vehicle, speed and heading of the object, all as a function of time.

It is recommended to have 360 degrees view on the environment. As the most relevant activities are the ones of the ego vehicle and the other traffic participants in front of the ego vehicle, there are, no strict requirements apply to the field-of-view of a sensor system for data collection. However, limited field-of-view might result in limitations regarding the scenario description. The description holds only for the field-of-view with which the data is collected and it cannot be extended beyond that, see the examples provided in Figure 9 and Figure 10. On-board or off-board sensors can be used to detect the environmental conditions (e.g. weather and light).

To complete the scenario description, data describing the *static environment* is required. This includes line markers, lanes and road edges Also a GPS signal with time and date stamp is required. In this way, the scenario description can be extended with map information to include e.g. the local road layout, the presence of intersections, sidewalks, cycle lanes, tunnels, the number of lanes etc.
The GPS signal and time stamp also support the collection of data regarding weather and lighting conditions, e.g. by making a reference

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[*] There are several reasons to use object data as input to StreetWise instead of raw sensor data:

- The conversion of raw sensor data to object level data is proprietary to the sensor manufacturers. By collecting object level data, the method of analysing this data becomes independent of the type of sensor, the sensor technology and the sensor make;
- The size of object level data is easily a factor of 100 smaller than that of raw data. Collecting object level data limits the amount of data that needs to be transferred from data collection vehicles, and it limits storage size.

to a meteorology database. Moreover, the signals from the vehicle's windshield wiper system and luxmeter are used to augment the scenario content regarding environmental conditions.

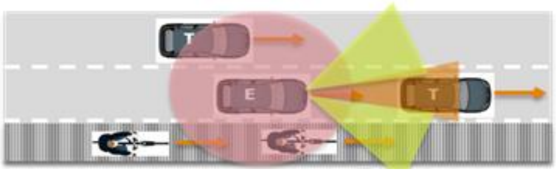

Figure 9a: Limited field of view

Figure 9b: Wider field of view (recommended)

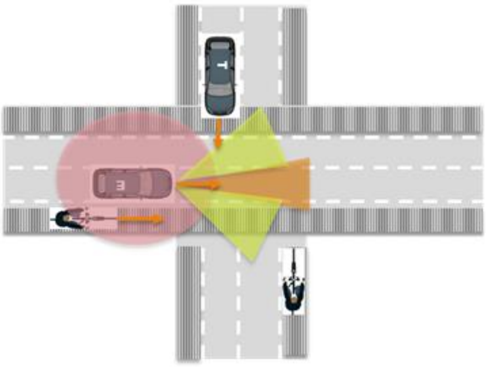

Figure 10a: Limited insufficient field of view

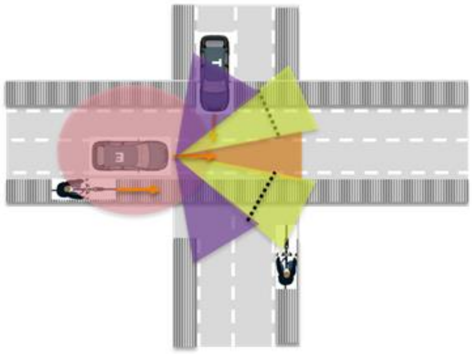

Figure 10b: Wider field of view (required in this situation)

3.3 Scenario identification and classification

Several data processing steps are distinguished for scenario identification and classification.

3.3.1 Event and activity detection

Events and activities, the smallest building blocks to describe the dynamic traffic in a scenario, play a central role in determining how relevant an identified scenario is for the scenario database, i.e. does a newly detected scenario add information to the database? As a first step towards scenario identification and classification, TNO develops techniques and algorithms to automatically detect events and activities in collected real-world (microscopic) traffic data. These are hybrid techniques that combine physical/deterministic models with data-analytics to detect events and activities hidden within terabytes of data.

The newly developed technique uses the domain expertise of vehicle dynamics modelling as well as data analytics including machine learning and artificial intelligence. The detection method not only provides an overview of the type and frequency of events and/or activities, but also the parameters describing their characteristics. For example, the maximum speed in lateral direction during a lane change is an indication for how aggressively the lane change is performed. Parameters describing the encountered activity (such as the maximum lateral speed in our lane change example) are stored with the detected activity.

Likewise, events and activities can be recognized in the description of the static environment, e.g. entering a tunnel, approaching an intersection with a view-blocking obstruction or passing a billboard. Similar, lighting and weather conditions in a scenario can be described as a sequence of events and activities, where in general one would expect that such activities are less dynamic and do not change as often as the activities recognized for the dynamic traffic. Where the time constants for the dynamic traffic are in the order of seconds, changes in lighting and weather conditions are usually in the order of minutes or even hours. In case of entering a tunnel or passing under an overpass, the change is rather drastic and lighting conditions will strongly vary within seconds.

3.3.2 Scenario mining

In scenario mining, the events and activities that are independently identified for the ego vehicle, the dynamic behaviour of the other traffic participants, the static environment and the conditions (see Figure 4), are combined to construct a scenario. An example is given in Figure 11, for a vehicle being overtaken while entering a tunnel.

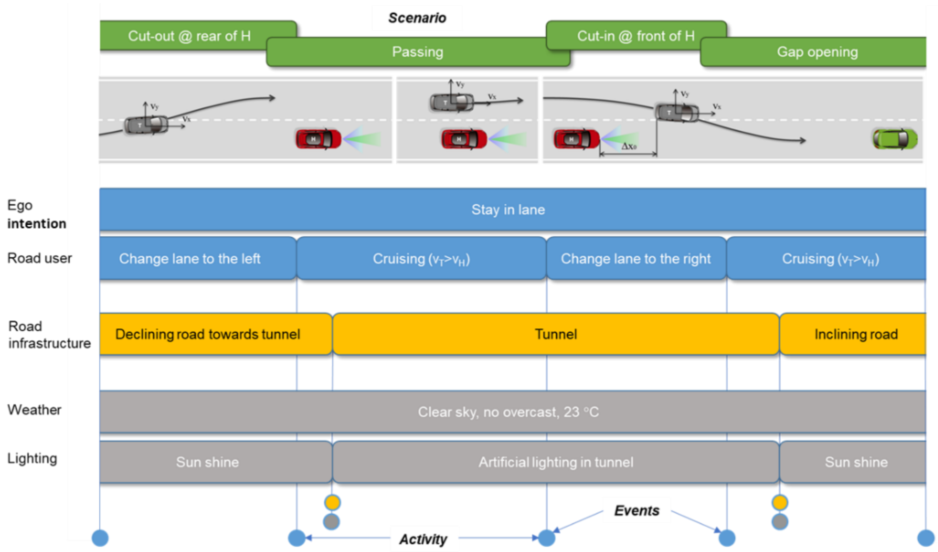

Figure 11: Activities and events for a vehicle that is being overtaken in a tunnel.

The figure shows blocks to indicate the activities that are identified for the scenario; the events are indicated with a circular marker. It is shown that activities might overlap, but that some relation between activities exists. In this case the lighting conditions are related to entering a tunnel (as part of the static environment). Similarly, the manoeuvres of the ego vehicle and the passing vehicle in the dynamic traffic description need to follow the road inclination and the curvature in the tunnel.
It should be noted that the start and end time of a scenario is a rather arbitrary choice. The example scenario of being overtaken by a vehicle while driving into a tunnel can be considered as the superposition of two scenarios overlapping in time: a scenario of driving through a tunnel and a scenario of being overtaken by a vehicle.

For the scenarios that are identified from the data collection on the public road, the relation between the activities, events and parameters, are all stored as metadata in the database. In this way, a full trip on the road can be reconstructed by retrieving and combining the related scenarios and its parameters from the database.

In Figure 12 and Figure 13, the results of the event and scenario mining algorithms in an example are shown. In this example the target is driving at constant speed in its lane. The ego vehicle initially accelerates until it is close to the target and brakes to match the speed of the target. Subsequently, the ego changes lane and accelerates to overtake the target.

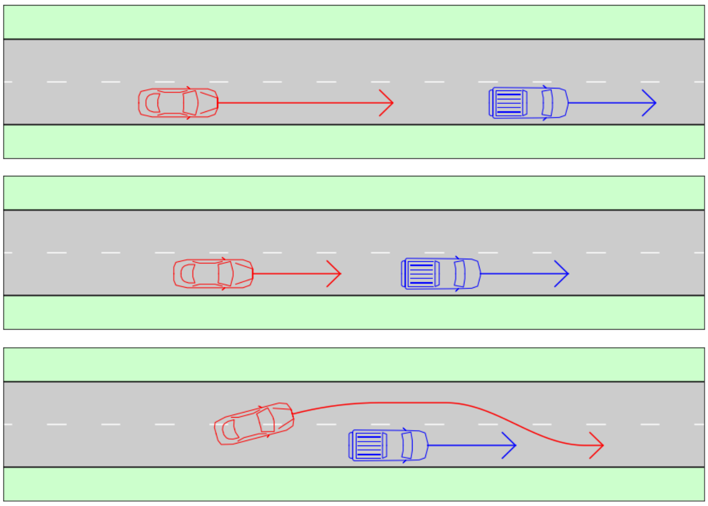

Figure 12: Schematic overviews of scenarios that resulted from scenario mining. In the first scenario (top), the ego vehicle (the red sedan) is approaching a target vehicle (the blue pickup truck). In the second (middle) and third scenario (bottom), the ego vehicle is following and overtaking the target vehicle, respectively.

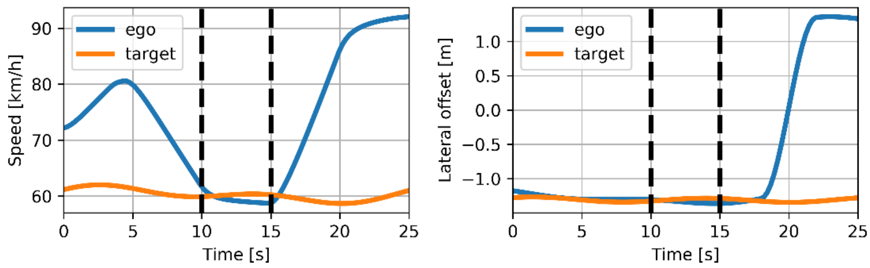

Figure 13: Speed and lateral offset (with respect to the centre of the road) of the three scenarios shown in Figure 12. The black dashed lines separate the three scenarios.

3.4 StreetWise scenario database

Currently, different activities are initiated and executed for Big Data collection and scenario mining, to continuously extend the StreetWise database with real-world traffic scenarios from Europe, Japan, China, US and Singapore. Only by combining the efforts of many different organizations, from industry to authorities, it becomes possible to provide a reliable view on scenarios that automated vehicles might encounter on the road and to show the differences in occurrence of scenarios for different cities, countries and continents. These differences are induced by differences in vehicle fleet, infrastructure layout, traffic rules, traffic behaviour and country specific conditions, e.g. related to weather and climate or even culture. To get access to this wealth of information, not only Big Data of sufficient quality has to be collected in all the different areas around the globe, but it has to be interpreted by classifying and parameterizing all scenarios that show up in this data.

3.4.1 Scenario storage

The StreetWise scenario database does not contain raw sensor data, but a parametrized model of the real world based on the sensor signals. Therefore, dependency of the stored scenarios on the sensor set with which the scenario was recorded is avoided. The only inherited feature of the sensors by the extracted scenarios is the sensor's field of view.

The fact that the stored scenarios do not contain the original sensor data brings several benefits.

- The original sensor data might be sensitive as it reveals the sensor setup and processing capabilities of a car. This is much less of an issue when only parameters of the models of the scenarios are stored. Whereas the original sensor data is unlikely to be shared among different parties, the resulting scenarios might be shared, such that the involved parties can benefit from each other.

- By condensing the information of all sensors into the least amount of parameters that describe the scenario within the error bounds of sensors, substantial reduction in storage volume is achieved.
- All the parameters of scenarios of a specific scenario class can be used to construct probability density functions. These probability density functions can be used to generate test cases that lead to probabilistic results [11]. Furthermore, it is possible, using the parametrized scenarios, to emphasize scenarios in which the system-under-test shows performance-critical behaviour without *a-priori* knowledge of what scenarios might be critical [11]. More information about the test case generation is presented in Section 3.4.3.
- The parametrized models of the scenarios allow for time interpolation. Hence, the stored scenarios can be used for any given sample time, regardless of the sample time of the original sensor data.

3.4.2 Insights in scenario occurrence and relevance

The characterization of scenarios with parameters opens possibilities for extracting parameter distributions for classes of scenarios. In this way, differences in scenario classes can be quantified. The parameter distributions for selected scenario classes will reveal nominal behaviour in a class, as well as less frequently occurring corner cases.

Clearly, the database does not only contain critical or near-critical scenarios; it predominantly shows the normal every day behaviour on the roads and the typical parameter ranges to describe this. This is information of utmost importance to support system developers in setting up realistic system requirements, and authorities and consumer organisations in providing test cases for safety assessment of the developed system before allowing the systems to be deployed in large fleets on the public road.

The mechanism of tagging and combining scenarios into scenario classes allows for investigation in how often certain scenarios occur on the road. Making a selection of tags, investigators can study differences between scenario classes and can establish the relevance of certain classes of scenarios and parameter ranges. This approach in using the scenario database is very similar to the way in-depth accident databases such as GIDAS [10] are used.

3.4.3 Test case generation

Main objective in using the scenario database is in selecting appropriate, relevant and realistic test cases for safety validation of automated driving systems. Different methods can be followed here:

1. System developers and system evaluators can simply *replay* selected scenarios or even a complete test drive. The exact same scenarios for dynamic traffic, the static environment and the lighting and weather conditions are retrieved from the database as

from the time they have been stored after analysis of a specific test or data collection drive. Such replay might be useful for model validation or for assessment of a specific problem collected from a test drive.

2. Since scenarios in StreetWise are parameterized, this allows for sampling of the probability density functions of the parameters to systematically generate candidate test cases for safety assessment. Figure 14 shows an example of the probability densities of the maximum deceleration in braking activities. The sampling procedure can be selected to emphasize safety-critical cases or to select a limited number of cases that are distributed over the complete operating area of an automated driving vehicle. It is also possible to target very specific scenarios e.g. by using a Monte Carlo technique for generating test cases that follow the probability density functions of selected parameters in the scenario data base. In this way, realistic test cases are generated that not necessarily have been observed in exactly this way on the road.
3. To generate very specific test cases, a technique such as importance sampling [24] can be used. Figure 15 shows an example of test cases generated using the importance density in parameter space. Similar as in Monte Carlo technique, a simulation model of the vehicle with the automated system is used. From the numerous possible test cases, it is impossible to judge upfront which cases are relevant. In that case, first the complete operating range of the automated system is simulated on a coarse grid covering the full ranges of the parameter distributions. Based on the simulation results of these cases, test cases can be selected in a fine grid in those areas that appear to be relevant for the system, e.g. critical cases for which the probability of a collision is high.

These different techniques result in a set of test cases for which the relevant ranges for the different parameters are covered, and all selected combinations of parameters result in a realistic test case: a relevant case that could occur in the real-world, but that not necessarily has been experienced during data collection. StreetWise provides these test cases for instance as input to the safety assessment framework. In this framework, procedures are followed to determine which test cases are simulated using virtual models and which test cases need to be tested physically, for virtual model validation and for providing essential test results in a limited number of selected points in the large grid of possible test cases.

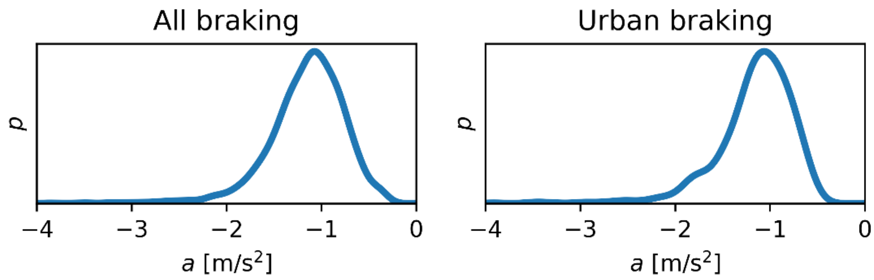

Figure 14: Estimated probability density functions of maximum deceleration values in braking activities based on all recorded braking activities (left) and the recorded braking activities in urban areas (right).

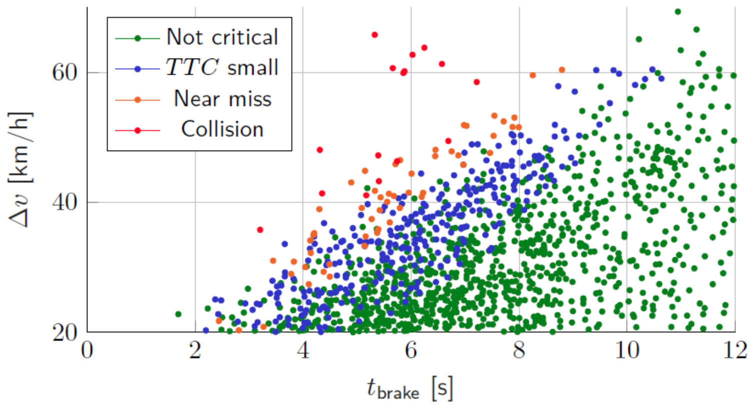

Figure 15: Parameter plot where each dot represents the simulation results of a test case. Red: collision, orange: near miss, green: not critical.

4 STREETWISE ROADMAP

In the previous sections, the current developments to evolve the StreetWise methodology have been described. The philosophy is explained and the steps from data acquisition to scenario and test case generation have been described. This section presents the research roadmap for the coming two years. A more detailed discussion is provided for the research topics that have been identified.

EXTENSION TOWARDS DIVERSE OPERATIONAL DESIGN DOMAINS

Using road types and operational design domains as guiding principle, TNO is building the automated algorithms to detect and classify the manoeuvres of the dynamic traffic participants. Obviously, for a highway type of road with multiple lanes separated by lane markers, with a single driving direction for all vehicles, without the presence of vulnerable road users, and no intersecting roads, the identification algorithms are different than for urban roads where the actors in the scenario may exhibit any type of manoeuvre from any direction at any point in time. Although the development of identification algorithms for highway manoeuvres still continues, a strong focus in 2018 - 2019 is on identification algorithms for urban environments, building upon StreetWise expertise developed for highway environments and models for the characterisation of manoeuvres of pedestrians and cyclists as for instance developed with the PROSPECT project [26]. Also technologies developed for automated valet parking applications are useful for making StreetWise fit for urban environments.

Interurban roads will follow by extending the application area of both highway and urban scenario identification algorithms.

SCENARIOS WITH MULTIPLE ACTIVE ACTORS

In StreetWise, the manoeuvres of multiple simultaneous actors in a scenario are treated as individual paths with an implicit dependency between the paths. These dependencies are not described or modelled. Fundamentally, the causality between the movements cannot be unambiguously derived from external observation of vehicles. It may be estimated. In the data driven approach of identifying manoeuvres out of real-world data, scenarios are stored in the StreetWise database without description of the causality of manoeuvres. In practice, this means the vehicle under test reacts to other road users, but the other road users do not react to the vehicle under test.

For constructing a multiple road user scenario out of events and activities of single individual actors, a superposition principle is assumed: any multiple actor scenario can be constructed out of multiple single actor scenarios. A theoretical framework for this approach is needed.

SCENARIOS FOR CONNECTED VEHICLES

Figure 16 shows the development roadmap for connected, cooperative and automated vehicles. StreetWise has been established having individual manoeuvring vehicles in mind, that receive their information on their environment from onboard sensor systems extended with a possible data flow provided by the infrastructure, such as traffic information or time-to-red for a traffic light. For connected vehicles, the wireless information input can be considered as another sensor in the complete sensor suite.

For a cooperating vehicle in a platoon, the vehicle receives high priority inputs that ask for immediate action of the vehicle's control and manoeuvring system. The latter type of information provides another dimension to scenario generation. We can distinguish scenarios that the platoon itself might encounter on the road, i.e. the scenarios that the lead vehicle runs into, and scenarios that consider the platoon itself due to the character of the platoon, i.e. vehicles cutting into the gap between the platooning vehicles. Test cases need to be specified that are only relevant for vehicles in a platoon as a system-of-systems before a safety assessment of platoons currently being developed can be completed.

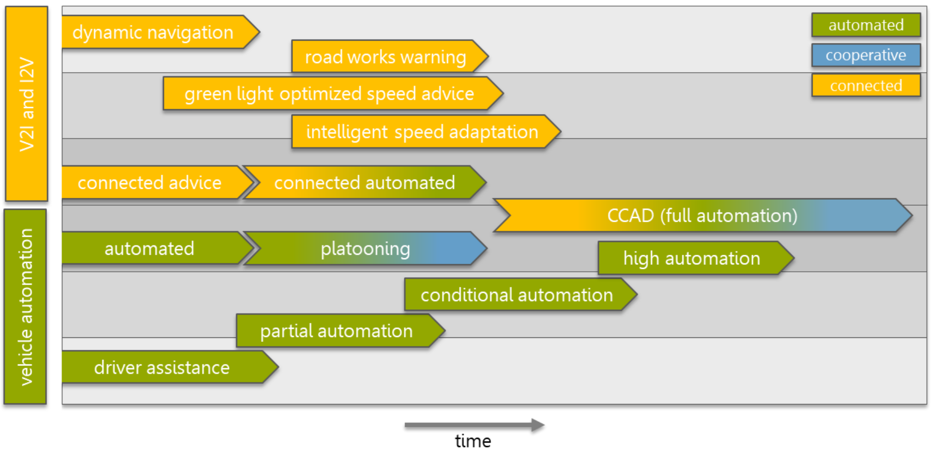

Figure 16 Abstracted roadmap for the developments towards full automated driving which in the view of TNO cannot be achieved without a cooperation between vehicles and a connection between vehicles and the infrastructure.

LARGE SCALE SCENARIO SHARING

Input to StreetWise is provided by datasets that are recorded from vehicles and processed to object level. These vehicles only qualify for providing input to StreetWise in case they have a state-of-the-art sensor set onboard with high level world modelling or sensor fusion capabilities for object identification and tracking. The data input to StreetWise can be extended by automated analysis of the data sets from vehicles that are provided for monitored deployment by

developers of automated driving vehicles; a period in which a safety driver is onboard and scenario and response data of the automated vehicle is collected to evaluate on-road safety.
The share of production vehicles that are equipped with a state-of-the-art sensor set and high grade sensor fusion capabilities is growing quickly as a result of the fast developments and innovations with regard to driver assistance systems such as Automated Emergency Braking, Adaptive Cruise Control, and Highway Pilot. For the future, TNO will investigate how to perform onboard scenario identification, such that vehicles may upload corner cases or less common scenarios into StreetWise. That would generate a wealth of statistical information, especially regarding differences in scenarios with location and time.

TEST CASE GENERATION

For the assessment of automated vehicles, a lot of emphasis is put on accidentology: from in-depth accident investigations, it is studied which accidents have happened in the past, including the course of events that led to the accident. This conventional approach is extremely valid when developing emergency functions such as crash avoidance and mitigation systems. These systems are supposed to only come into action when a critical event is imminent. This is a balancing act between preventing false-positive responses (taking an emergency response when the situation is not critical) and being sensitive for true-positive situations (a critical situation occurs and the vehicle is taking appropriate action). In normal driving conditions, such vehicles continuously take action in anticipation to the environment and the scenarios that they encounter, to prevent that normal conditions evolve into a critical situation. Additionally, similar to driver assistance systems, automated vehicles will need to provide an emergency response to prevent that a critical situation escalates into an accident. For higher levels of automation, the parameter range to trigger such emergency response is larger than that for driver assistance systems as the automated system can no longer rely on a driver that is capable to take over control.
A procedure is needed to generate an appropriate and relevant set of test cases out of the collected scenarios. This procedure should distinguish between these two testing regimes, providing also test cases that are not critical to start with (‘nominal’ or ‘comfort’ test cases).

COMPLETENESS OF THE SCENARIO DATABASE

To draw conclusion on how an automated vehicle would perform in real-world traffic, it is necessary to know how representative the scenario database is of the real world. Therefore, it is important to quantify how complete the scenario database is. At the moment, this is still an open question [12][25] .

Within StreetWise, measures are developed for quantifying the completeness of the obtained scenarios and the completeness of the generated test cases. These measures will describe to which extent the scenario database reflects the variety of scenarios that can be encountered in real-world traffic. This, in turn, enables stronger claims regarding the road-worthiness of the assessed vehicles.

SAFETY ASSESSMENT FRAMEWORK

One major objective of StreetWise is to provide well-founded, relevant and realistic test cases for the assessment of automated driving systems, as well as for advanced driver assistance systems. As StreetWise uses real-world data for the generation of scenarios and analyses the rate of occurrence of such scenarios and its associated parameters, it is possible to provide a grid of test cases that is valid as it covers the complete relevant operating area of the automated driving system. This selection of scenarios is representative and fair as scenarios are technology independent and similar for all systems proposed for a specific application and area of deployment.

Test cases are not only provided for a final assessment before road approval, but also at intermediate stages of development, so that developers of automated driving systems can use this relevant information in their development process.

Due to the expected high number of test cases that are necessary for achieving an acceptable confidence in a vehicle-under-test, it will be infeasible to provide results of a physical test for each of these test cases in an assessment. Consequently, many cases will need to be covered with virtual simulations and various tools are on the market to perform such simulations. Physical tests on a test track - or even on the road - are still required for spot checking and for validation of the simulation models that are being used. Yet, no method is currently available to decide which test cases out of the large number of test cases need to be physically tested and for which test cases simulation results are sufficient. TNO is investigating this selection problem, e.g., in view of the so-called grid method that might be applied by Euro NCAP [27] to limit the number of AEB car-to-car tests with variations in overlap, approaching angle and vehicle speed. This will also need to consider how to handle the even larger number of possible variations for the assessment of automated driving systems.

Within the Centre of Excellence for Testing & Research of Automated Vehicles – NTU (CETRAN) in Singapore, a framework for operational safety evaluation of automated vehicles has been developed to come to a clear and unambiguous road worthiness approval procedure for automated vehicles before deployment on Singapore roads. The framework (see Figure 17) shows how data is used to generate test cases as input for virtual and physical safety validation [25]. How to translate the results of virtual simulations and physical tests in a safety assessment is subject of current investigations. TNO, as a partner in CETRAN, uses the StreetWise methodology and its expertise in testing and safety evaluation for the automotive industry to support this research.

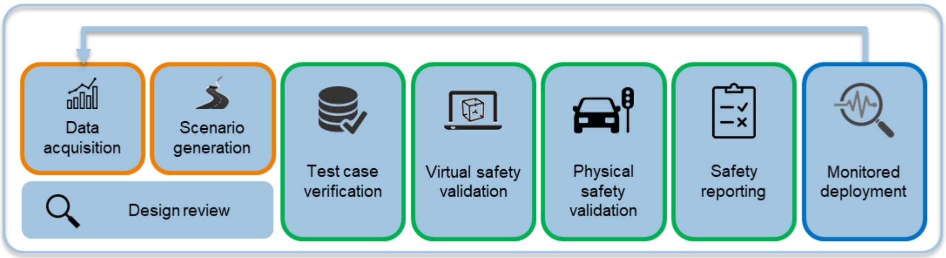

Figure 17: Scenario-Based Safety Assessment Framework for Automated Vehicles (CETRAN)

An important step that is foreseen in the framework is the monitored deployment of automated vehicles once they successfully passed the safety assessment and are allowed to drive on public roads, possibly restricted to certain areas and/or conditions. During this deployment phase, the developer of the automated vehicle is required to upload driving data to allow for monitoring the behaviour of the automated vehicle. This is implemented for two reasons:

- Also after completion of the assessment pipeline, road authorities need to be able to monitor safety continuously.
- The uploaded data is, after anonymization, fed back to the data acquisition element in the framework.

This feedback loop allows for continuous extension and improvement of the scenario database, while also enabling adaptation to changes in the mobility system, e.g., as a result of deployment of new technologies. This has the fundamental advantage that the safety assessment procedure itself is further fine-tuned based on experiences with the operation of automated vehicles in the field.

5 CONCLUSION

StreetWise is a data-driven methodology that provides real-world scenarios and test cases for the development and assessment of advanced driver assistance systems and (connected) automated driving systems. The core of the method is a database in which all parameterized scenarios are stored that have been identified from driving data that is collected from the various fleets of data collection vehicles. This can be either test vehicles, prototype vehicles or production vehicles that drive on the public road collecting data with their state-of-the-art ADAS or (C)AD sensor sets.

The scenario database is accessible to participants in StreetWise. They temporarily provide their – confidential – object level data to TNO for scenario mining. As an independent and not-for-profit organization, TNO uses its automated scenario mining algorithms to extract scenarios and scenario parameters to update and extend the scenario database. After scenario mining, the data is permanently deleted from TNO's systems.

This way of working is a giant leap forward in pre-competitive cooperation in reusing and sharing valuable scenario information collected in test drives, without running into showstopper discussions on intellectual property or confidentiality issues associated with the raw data. It enables participants in StreetWise to study differences in scenario characteristics for different cities, countries and continents, without the need to run their own large testing or data collection campaigns in each of these areas, while keeping their driving data confidential.

Since all scenarios in the StreetWise database are parameterized, a relevant selection of scenarios for testing a specific system is easily made using a database query. The database provides the scenario selection with an overview of the probability density functions of the parameters showing how likely a certain measured value of a parameter is found in the selection. These parameter distributions allow for an analysis of the relevance of scenarios, e.g., for nominal cases that occur frequently or for corner cases in the tail of the parameter distributions that happen rarely.

From the scenario selection, test cases are generated using different options in sampling parameter values, such as simply replaying the scenario as encountered on the road without sampling, Monte-Carlo simulation or importance sampling. Test cases can be ported as input to any simulation tool chain using the OpenSCENARIO and OpenDRIVE format, which is a generally recognized open standard [12]. The test cases can also be provided in other formats.

In the methodology of StreetWise, it is important to collect scenarios based on a large variety of data sources. Currently, partners are collecting data in different countries, but also on different type of road, with interest in both highway and urban applications. This helps the scenario database to grow quickly, however, practically it will never be complete, even if the scenarios in the database are based on millions of kilometres of driving. Over time, driving behaviour and interactions will evolve with higher penetration of ADAS and AD. The number of kilometres in the database is a poor metric for completeness. StreetWise provides more advanced metrics. The new scenario detection rate is a first indicator. Since StreetWise stores parameterized scenarios, the parameter distributions allow to provide insight in the level of completeness, or more specifically the change in parameter distributions with the addition of more kilometres of data. Within StreetWise, the scenario definitions and the related scenario mining techniques are agnostic to the automated driving technology or the applied sensor technologies. Scenario specification is only limited by the field-of-view and the quality of target identification of the sensor system onboard of data collection vehicles. A scenario cannot be reliably described outside the field-of-view and for this reason, the sensor system limitations are stored in the database meta information with a reference to the resulting scenarios. Through off-line analysis, scenario mining algorithms can ‘look into the future’ and have a higher level of confidence than real time analysis would provide. Herewith, TNO has developed a scenario mining methodology in StreetWise that is sustainable for the future, able to keep up with the fast developments in both sensor technologies and automated driving technologies. It is expected that StreetWise is capable to show the impact of the fast growing fleet of automated vehicles on scenario parameter distributions over time. That is valuable input for the automotive industry, research institutes, academia and authorities to steer new developments and policy making processes for the safe introduction of new and future automated driving technologies onto the public road.

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