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Adaptive level lane estimation policy of automotive systems moving within arbitrary road networks

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Abstract—The problem of a Vehicle Positioning System (VPS) is addressed. A specifically developed approach based on the cause-and-effect principle defines a closed-loop policy determining the lane level location of a sensor equipped vehicle moving within arbitrary road networks. After exploration of processed data provided by a smart camera and a laser detector appropriate information is routed to the decision making scheme. Based on identification of particular mobile objects circulating within the current and/or opposite flow the vehicle lane level location is determined when the car circulates within highway stretches or urban areas. Contrary to other schemes no additional investment on costly devices and complementary tools is required. The reduced computational complexity makes the deployment of the suggested methodology efficient for embedded technologies and can be utilized independently or as a complementary tool. Major restrictions of previous works of the same authors requiring divided freeway infrastructures are now overcome. A first appraisal of the system effectiveness is achieved through realistic simulation data fed by complex real recordings. Multiple drawbacks involved with information collected by professional driver behavior are minimized. Three case study scenarios, associated with different traffic and light intensity, resulting to a varying sensor behavioral functioning are considered. Adequate metrics appraise the efficiency of the suggested methodology.

Index Terms—Highly Automated Driving Functions (HADF), lane identification, real time path and target tracking control, data mining, road navigation, autopilot perception, environment perception, adaptive policy for smart sensor utilization

I. INTRODUCTION

Smart decision making and control skills significantly contribute to efficient performance of any automotive structure. Advanced Vehicle Control System (AVCS), Advanced Driver-Assistance Systems (ADAS), Car Navigation System (CNS), Advanced Highway System (AHS) all contribute to optimal decisions for autonomous car driving and safety, requiring multiple information involving vehicle positioning. Additionally, fields of traffic estimation and control necessitate similar information. Connected vehicles can be used as mobile sensors and communicate information on traffic [1], [2]. Precise path-tracking control may influence vehicle itineraries, reduce travel times and positively impacting traffic management policies. Given a series of observations, simultaneous localization and mapping (SLAM) methods constructing or updating a map are often associated with increased computational power [3]. Consequently, embedded systems cannot fully implement SLAM. Recent studies on vehicle assistance guidance are employing expensive HD map approaches [4], [5] which should be

additionally updated with every infrastructure modification. Other assistance systems utilizing dual frequency carrier phase differential GPS (DGPS) in association with HD maps [6], [7], [8]. Nevertheless, multiple errors may interfere originated to satellite dysfunctions. There is no possibility of correcting the carrier phase ambiguities which need to be always approximated [9]. The initialization time of about 20 minutes need for the float position to be converged into centimeter accuracy limits performance of GNSS/GPS data in systems involving real time data. Error mitigation approaches are developed in [10], [11] the performance of which depends upon the HD map quality. Radio frequency identification schemes (RFID) [12], [13], lane detection algorithms based on Hough transform [14], [15], [16] aiming at lane identification are also associated with increased complexity and errors. A lane estimation approach for urban areas is presented in [17] employing visual lane marking detection, radar, and GPS, and a digital map describing road geometry and topology.

This paper addresses the spatio-temporal problem of dynamic lane level identification of a sensor equipped vehicle moving within arbitrary road networks. The suggested policy makes use of minimal information available by a laser detector and a smart camera. The total number of lanes associated with the related road segment is provided by a GPS cartography. Furthermore, the proposed scheme is significantly advanced regarding previous works as in [18] where an elementary approach is presented requiring the existence of a physical road separator between the two opposite traffic directions. The new approach covers any type of freeway and arterial infrastructure. Despite the increased flexibility and contrary to various similar approaches frequently associated with complicated structures, low computations are now required due to the reduced complexity of each conceived algorithm. Consequently, the new decision-making scheme would be appropriate for embedded applications, employed independently and/or as a complementary decision approach operating in association with other methods. Furthermore, the proposed methodology is appraised by means of realistic simulation data based on real recordings. As a result, the multiple biases introduced by ideal driving behavior provided when drivers are aware of trip registrations are now significantly diminished.

The remainder of the paper is organized as follows. The problem to resolve is introduced in §II. The principle and mathematical model of the lane decision policy are defined

in §III. §IV appraises the performance of the lane detection algorithm. The employed data and considered scenarios are discussed. Quantitative and qualitative statistical analysis measurements are evaluated. Finally, §V resumes the main findings and contributions of the research.

II. PROBLEM FORMULATION

Aiming at defining the lane level of a vehicle within any time t and position $p(t)$ of the related trajectory a first approach of an adaptive feedback policy is going to be introduced. Sensors reveal a wealth of information on the tracked objects and vehicle state. At observation instant t a laser sensor scans multiple mobile and immobile objects within a multi-plane and long range vision angle. Each detected entity is associated with an ordered pair of lateral and longitudinal coordinates with respect to the current position of the reference vehicle where the system origin is located at detection time t .

Let $N(t)$ describe the number of all captured observations at time t , then the set of the relative reference points \mathcal{O} can be determined at time t .

$$\mathcal{O}(t) = \{p_i(t) = (x_i(t), y_i(t)), i = 1, \dots, N(t)\}. \quad (1)$$

$$\text{card}(\mathcal{O}(t)) = \begin{cases} > 0, & \text{if } N(t) > 0 \\ 0, & \text{otherwise.} \end{cases} \quad (2)$$

Eq. (2) underlines that set \mathcal{O} may become very large or even empty. As laser sensors are associated with a long and wide detection range number $N(t)$ can be very big or become zero depending upon the present environmental context of the car, sensor failures etc. Data fusion techniques (employing available information from complementary technologies) or missing signal estimation schemes for noisy and irregular data are some alternatives for an efficient handling of an empty observation set \mathcal{O} at a time t . A signal estimation model based on artificial neural network programming is under development but it is not presented in this work. Additionally, disturbing objects may imply misleading results. An intelligently determined observation set comprised of *well selected* objects contributes to the performance of the lane identification algorithm.

A set of qualitative and quantitative constraints can be associated with each detected object allowing a finest definition of the observation set. Hence, if Q and Q' denote the number of the considered qualitative and quantitative constraints, then sets \mathcal{C} , \mathcal{C}' can be determined

$$\mathcal{C} = \{c_q, q = 1, \dots, Q\}. \quad (3)$$

$$\mathcal{C}' = \{c'_q, q = 1, \dots, Q'\}. \quad (4)$$

As a result a restricted detection set can be constructed

$$\mathcal{O}_1(t) = \{p(t) \in \mathcal{O}(t) \text{ s.t } c(p(t)) \text{ satisfied } \forall c \in \mathcal{C} \cup \mathcal{C}'\}. \quad (5)$$

Let p_r denote the reference point of the considered vehicle, that is $p_r(t) = (0, 0)$ for any time instant t , $v(p(t))$ the speed of detection object p at time t . Furthermore, if $(\mathcal{D}_{\epsilon_1}, d_{\epsilon_1})$ and

$(\mathcal{D}_{\epsilon_2}, d_{\epsilon_2})$ two ordered pairs where ϵ_1, ϵ_2 can be any desired positive numbers, $\mathcal{D}_{\epsilon_1} \subset \mathcal{O}$, $\mathcal{D}_{\epsilon_2} \subset \mathcal{O}$ and $d_{\epsilon_1}, d_{\epsilon_2}$ are metrics on $\mathcal{D}_{\epsilon_1}, \mathcal{D}_{\epsilon_2}$ then

$$\mathcal{D}_{\epsilon_1}(t) = \{p(t) \in \mathcal{O}(t) \text{ such that } d_{\epsilon_1}(p(t), p_r(t)) \leq \epsilon_1 \text{ and } v(p(t)) > 0\}. \quad (6)$$

$$\mathcal{D}_{\epsilon_2}(t) = \{p(t) \in \mathcal{O}(t) \text{ such that } d_{\epsilon_2}(p(t), p_r(t)) \leq \epsilon_2 \text{ and } v(p(t)) < 0\}. \quad (7)$$

Equations (6) and (7) describe detections located within a desired area in a neighborhood of the reference vehicle moving either within the same traffic flow or following the opposite direction. Parameters ϵ_1 and ϵ_2 can be appropriately adjusted from one time t to another so as sets $\mathcal{D}_{\epsilon_1}(t)$, $\mathcal{D}_{\epsilon_2}(t)$ become neither empty nor very large.

Let m_d denote the total number of lanes in the direction of the considered car (*ego vehicle*), j the candidate lane where the system origin is placed with $1 \leq j \leq m_d$, $y_{i,j}^l(t)$ the y -coordinate of the left boundary of lane i regarding lane j at time t and $y_{i,j}^r(t)$ the y -coordinate of the right boundary of lane i regarding lane j at time t , for any i, j such that $1 \leq i \leq j \leq m_d$. Allow w to denote the lane width and d_l, d_r the distance between the ego vehicle and the left and right lane boundaries respectively. Hence, the values of $y_{i,j}^l$ and $y_{i,j}^r$ at time t can be computed by the following equations

$$y_{i,j}^l(t) = \begin{cases} d_l(t) + (j - i) \times w, & \text{if } i < j \\ -(d_r(t) + (i - j - 1) \times w), & \text{otherwise.} \end{cases} \quad (8)$$

$$y_{i,j}^r(t) = \begin{cases} d_l(t) + (j - i - 1) \times w, & \text{if } i < j \\ -(d_r(t) + (i - j) \times w), & \text{otherwise.} \end{cases} \quad (9)$$

Remark 1: For simplicity a fixed value of the lane width is considered equal for all lanes within the related road segment. If each lane i is associated with its proper width w_i , it suffices to replace w by w_i in Equations (8) and (11).

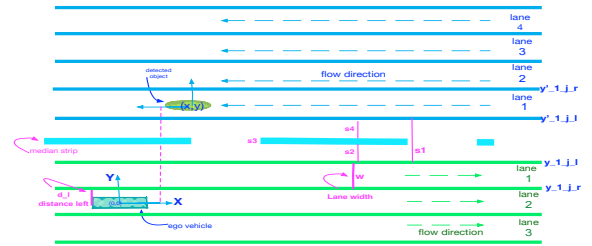


Fig. 1. Vehicle environment

Let s_1 denote the distance between the left boundary of the first lanes within the two opposite traffic flow directions (see also Fig. 1), with s_1 any positive number. If m_o denotes

the total number of lanes in the opposite direction of the ego vehicle, then the lane boundaries of the opposite road segment $y_{i',j}^l$ and $y_{i',j}^r$ at any time t can be computed regarding the candidate lane j from the following equations:

$$\begin{aligned} y_{i',j}^l(t) &= y_{1,j}^l(t) + s_1 + (i' - 1) \times w \\ &\quad \forall i' = 1, 2, \dots, m_o, \\ &\quad \forall j = 1, 2, \dots, m_d. \end{aligned} \quad (10)$$

$$\begin{aligned} y_{i',j}^r(t) &= y_{i'+1,j}^l(t) \\ &\quad \forall i' = 1, 2, \dots, m_o, \\ &\quad \forall j = 1, 2, \dots, m_d. \end{aligned} \quad (11)$$

Remark 2: The distance s_1 between the two opposite flows may become a number close to zero especially in urban areas.

III. LANE LEVEL ALGORITHM - STRICT APPROACH

A *strict* policy determining the level lane position of the ego vehicle is proposed by detecting appropriate mobile entities. Three complementary approaches are employed regarding the vehicle followed direction. Thus, objects moving within the opposite traffic flow and/or current direction of the ego vehicle are utilized. Some common cases where the later two choices are privileged concern one way road infrastructures, decision instants related to missing information due to inadequate sensor information or traffic context or when multiple feasible responses are provided by the former scheme.

Denote p_{d_M} and p_{d_m} the largest and smallest elements of set \mathcal{D}_{ϵ_2} , that is

$$\begin{aligned} p_{d_M}(t) &= (x_{d_M}(t), y_{d_M}(t)) \\ &= \arg \max_{y(t)} \mathcal{D}_{\epsilon_2}(t). \end{aligned} \quad (12)$$

$$\begin{aligned} p_{d_m}(t) &= (x_{d_m}(t), y_{d_m}(t)) \\ &= \arg \min_{y(t)} \mathcal{D}_{\epsilon_2}(t). \end{aligned} \quad (13)$$

A candidate lane j will be considered if points p_{d_M} and p_{d_m} satisfy the following two equations

$$\left| y_{1,j}^r(t) - y_{m_o,j}^l(t) \right| - \sigma_1 < |y_{d_M}(t) - y_{d_m}(t)| \quad (14)$$

$$|y_{d_M}(t) - y_{d_m}(t)| < \left| y_{1,j}^l(t) - y_{m_o,j}^r(t) \right| + \sigma_2 \quad (15)$$

where parameters $\sigma_1 \simeq 0$ and $\sigma_2 \simeq 0$ represent small positive numbers.

Remark 1: The term *strict* has the sense that the suggested methodology utilizes only object detections without any use of other approaches such as lane change observations which could considerably improve the resulting performance of the algorithm. The main purpose of this study is to examine the potential of the introduced methodology regarding reliability and robustness. In a final project it would be wiser to associate multiple approaches not presented in this paper.

Remark 2: If set $\mathcal{D}_{\epsilon_2}(t) \neq \emptyset$ then sets $\arg \max_{y(t)} \mathcal{D}_{\epsilon_2}(t)$ and $\arg \min_{y(t)} \mathcal{D}_{\epsilon_2}(t)$ are also nonempty and bounded. Hence points $p_{d_M}(t)$, $p_{d_m}(t)$ exist.

Remark 3: Parameters σ_1 and σ_2 are required for computational precisions due to sensor sensitive behavior in particular environmental contexts. Furthermore, parameter σ_1 allows perceptible movements within the the two last lanes of the opposite flow to be considered. Equivalently, parameter σ_2 represents movements within the boundary lanes of the two opposite flows when no road separator exists within the related road infrastructure.

Consider now reference points p'_{d_M} and p'_{d_m} such that

$$\begin{aligned} p'_{d_M}(t) &= (x'_{d_M}(t), y'_{d_M}(t)) \\ &= \arg \max_{y(t)} \mathcal{D}_{\epsilon_1}(t). \end{aligned} \quad (16)$$

$$\begin{aligned} p'_{d_m}(t) &= (x'_{d_m}(t), y'_{d_m}(t)) \\ &= \arg \min_{y(t)} \mathcal{D}_{\epsilon_1}(t). \end{aligned} \quad (17)$$

If $\sigma_3 \simeq 0$, $\sigma_4 \simeq 0$ and $\sigma_5 \simeq 0$ represent small positive numbers then candidate lane j will be considered if both equations are satisfied

$$y'_{d_M}(t) \in [y_{1,j}^l(t) - \sigma_3, y_{1,j}^r(t) + \sigma_4] \quad (18)$$

$$y'_{d_m}(t) \in [y_{m_d,j}^l(t) - \sigma_5, y_{m_d,j}^r(t)]. \quad (19)$$

Remark 4: Parameters σ_3 , σ_4 , σ_5 allow vehicle movements within related neighbor lanes to be taken into consideration.

Another criterion for considering candidate lane j involves reference points p_{d_M} and p'_{d_m} . If (14) and (19) are simultaneously satisfied by the y coordinate of observations p_{d_M} and p'_{d_m} respectively at time t then lane j can be considered as candidate.

IV. PERFORMANCE ASSESSMENT

A. Case Study

The lane level algorithm described in §II estimating the current vehicle lane position is going to be evaluated. Within this goal, detailed simulation data fed by multiple real recordings are going to be utilized. Professional drivers being aware of the realized registrations present unrealistic behavior which often results to untruthful information. Moreover, frequently occurring irregular situations are missing. Appropriate data treatment is necessary for obtaining rational driving contexts.

A trajectory starting at Paris, Rue de l'Université, reaching Versailles and then returning back to Paris at Charles de Gaulle-Étoile is considered as depicted in Fig. 2. The trip is consisted of urban road segments as well highway stretches involving rich road infrastructure and complex traffic conditions. Three different scenarios are considered the duration of each is 68 minutes (4,080 seconds). The first scenario occurs in the afternoon from 14.53 to 16.01, the second one is also realized within the same time period but under different meteorological

and traffic conditions involving lower sunlight intensity and resulting to a different sensor functioning. Finally, the third scenario realized later from 17.53 to 19.01 is associated with decreased light of different nature and slightly increased traffic density allowing the trip to have the same duration as in the two previous scenarios. Each case will be separately appraised.

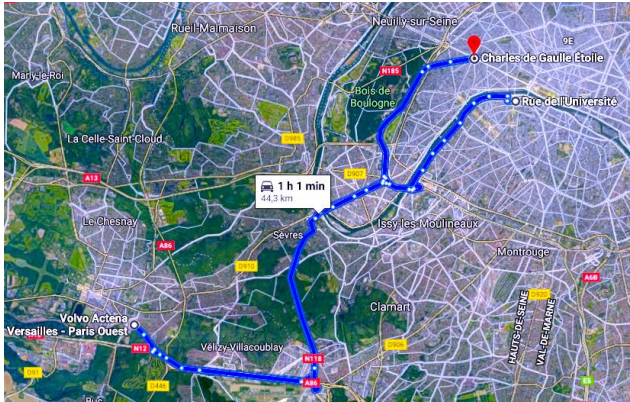


Fig. 2. Vehicle trajectory.

B. Measuring Accuracy

Within every sensor detection (related frequency of 25Hz) the previously introduced lane level identification policy is called estimating the lane position of the ego vehicle. Figs. 3, 4 and 5 depict the estimated and real value of the followed lane id over time for the three considered scenarios. One observes that for the majority of the trip duration the real value (green plot) coincides with the calculated one (red curve for the first two scenarios and cyan plot for the third one). A deeper analysis implies that most of the erroneous responses are due to imprecise sensor information. Consequently, the relatively small mistakes on observations as provided by the laser sensor (LIDAR) affect the involved computations returning neighbor adjacent lanes as the current vehicle position. In case of important inaccurate information returned by the laser detector distant lanes could have been responded by the decision scheme. However, this situation can be handled by improving the laser technology requiring increased precision on information process and by adopting complementary decision policies. Thus, a lane change policy would have detected that the lane level of the considered car wouldn't have changed. However, as previously discussed no alternative estimation scheme is employed in this work. The main purpose of this study is to evaluate independently the presented methodology.

C. Sensor Information Quantification

With a laser sensor frequency of 25Hz, during the 4,080 seconds of trip duration, 102,000 times detected observations are returned. The suggested decision approach is employed only when the utilized information corresponds to valid signals. Table I illustrates the total number of times where valid detections are returned by the laser sensor, for each one of the three scenarios. One sees that the best performance is obtained

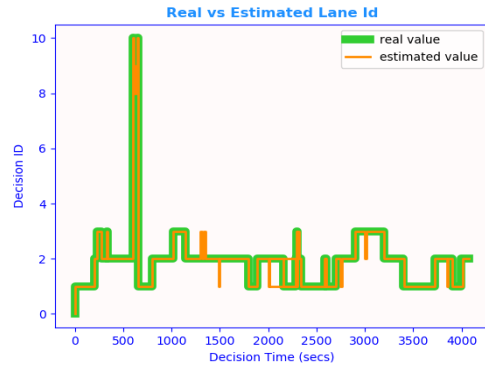


Fig. 3. Vehicle lane trajectory-scenario 1

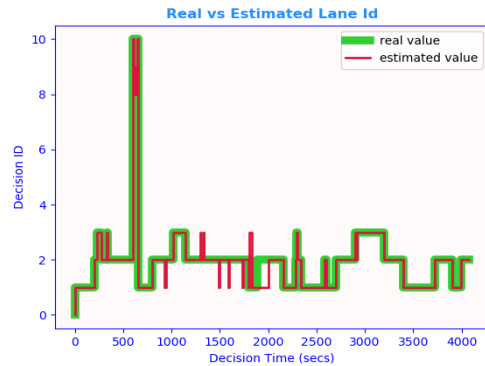


Fig. 4. Vehicle lane trajectory-scenario 2

by the trip realized between 5.53 and 7.01 PM associated with reduced sunlight. However, multiple factors interfere in the sensor behavior except the sunlight.

Figs. 6, 7 and 8 present a classification of invalid information according to the type of the sensor. As the proposed decision approach utilizes laser and camera detections, the percentage of erroneous data is presented for each scenario and for both the laser sensor and smart camera. At a first sight one could affirm the camera sensitivity to sunlight as

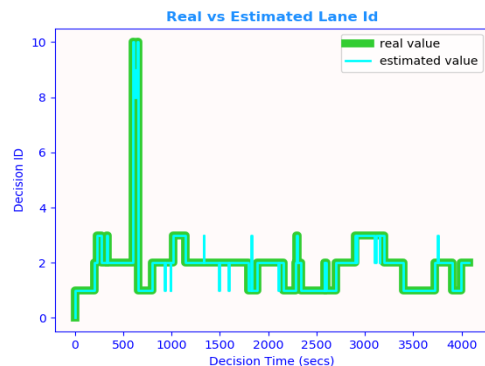


Fig. 5. Vehicle lane trajectory-scenario 3

TABLE I
VALID SENSOR INFORMATION

Scenario ID	Valid Detections %	Number Valid Detections
1	85.8	87,516
2	92	93,840
3	94	95,880

well the laser dependence upon the traffic density. However, the corresponding statistics concern the three considered case study configurations and it would be preferable if no definite conclusions are drawn at the current stage of the work.

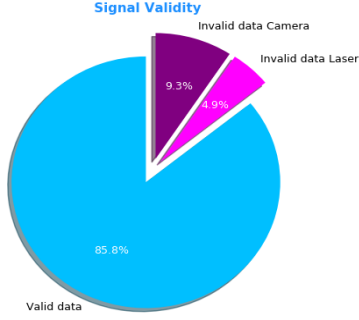


Fig. 6. Invalid data classification-scenario 1

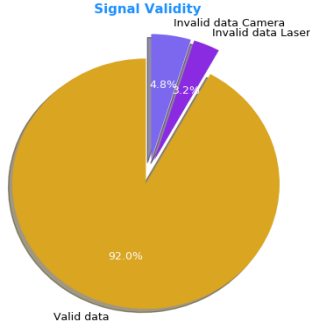


Fig. 7. Invalid data classification-scenario 2

D. Response Frequency and Error Quantification

Within every sensor detection utilized data are analyzed and if they considered valid they are next provided to the decision making policy for determining the lane level position of the ego vehicle. The current version of the suggested lane identification scheme provides a response when the sensor functioning is judged as acceptable as well a unique feasible response results. Moreover, the present methodology may provide no response if values ϵ_1 , ϵ_2 do not exist such that the $\arg \min$ and $\arg \max$ elements of sets \mathcal{D}_{ϵ_1} and \mathcal{D}_{ϵ_2} satisfy (14) and (15), (18) and (19), (14) and (19).

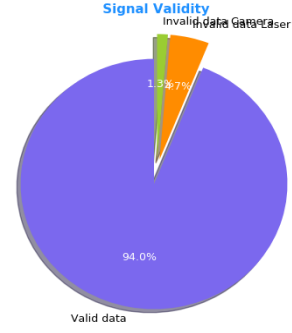


Fig. 8. Invalid data classification-scenario 3

Figs. 9, 10 and 11 illustrate the response frequency of the employed lane identification policy for each one of the three considered scenarios. Thus, for the first scenario where 90% of the detection time was associated with valid information, the involved error of the ego-vehicle lane estimation is of 5.1%. The second case study was associated with valid information during 92.15% of the total travel time and for which 4% of the returned responses were mistaken. Finally, for the last scenario, a wrong lane id was computed during 3% within valid sensor functioning (95%). Similarly to previous statistical results, at this stage of the study the presented numbers should not lead to final conclusions as much more cases need to be further examined.

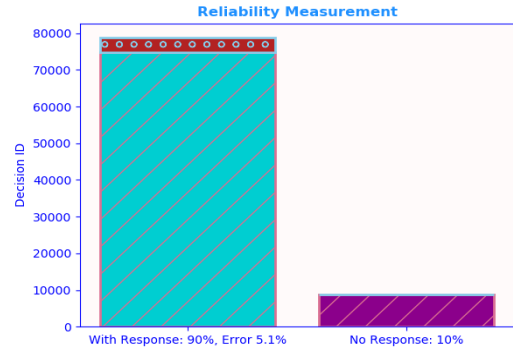


Fig. 9. Response frequency-scenario 1

V. SUMMARY

This paper presents a part of an ongoing research study of a spatio-temporal problem aiming at identifying the level lane position of a sensor equipped vehicle at any time of the trip occurring within arbitrary road networks. An *adaptive closed loop* decision policy is developed requiring minimum local information resulting from sensor outputs, a laser detector and a smart camera. With every detection *suitable* validated data are analyzed and then provided to the suggested scheme. The vehicle lane position will be determined after identification

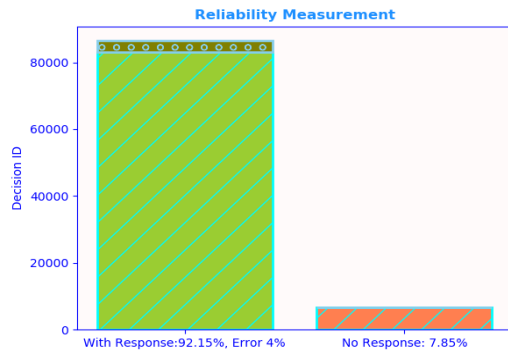


Fig. 10. Response frequency-scenario 2

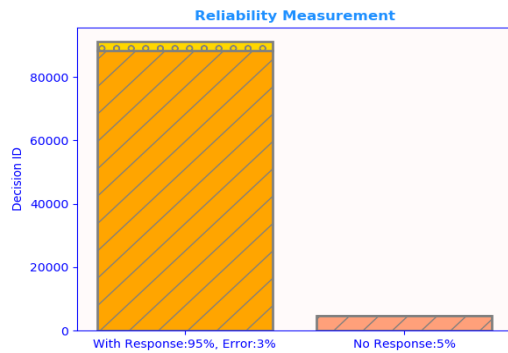


Fig. 11. Response frequency-scenario 3

of *appropriate* mobile objects moving within the opposite flow and/or the current vehicle direction. The location of the considered observations is estimated by means of a well determined Cartesian coordinate system *dynamically* defined for each candidate lane representing the potential position of the ego vehicle. A low computational complexity is associated with the whole scheme allowing for an efficient embedded application. This study overcomes major limitations of previous versions developed by the authors necessitating the existence of a road separator between the two opposite traffic flows. Any type of freeway infrastructure as well urban areas can be covered. A strict version of the developed methodology is deliberately presented estimating the vehicle lane after calculations utilizing object detections. No complementary schemes are employed such as lane change behavior or estimation of missing sensor signals. The ultimate goal of this study is a first evaluation of the proposed algorithms when they are employed independently instead of a final lane identification policy.

A first appraisal of the suggested scheme is presented, applied on three scenarios created by simulation data fed by real recordings. Thus, multiple biases generated by drivers being aware of the registration procedures (adequately adapting their behavior) are reduced and consequently realistic information is now available. Each one of the three considered case studies corresponds to a different sensor functioning

allowing the appraisal of the developed policy within various contexts. The same journey is considered in all scenarios, starting at Paris, arriving at Versailles and then returning back to Paris. A different trajectory path consists each one of the two way trip. A rich road infrastructure is involved as well varying and complex traffic conditions during the entire journey. A profound statistical analysis measures the response frequency and accuracy of the employed decision approach while a data qualification and classification is presented per employed sensor type. Nevertheless, it should be accentuated that at the present stage of work, no definite conclusions should be drawn regarding the provided numerical values quantifying the system performance. More scenarios are under consideration involving various trajectories, traffic contexts and thus a representative sensor functioning.

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