2010 IEEE Intelligent Vehicles Symposium
University of California, San Diego, CA, USA
June 21-24, 2010

Assessment of Safety Levels and an Innovative Design for the Lane Change Assistant

Mark Roelofsen, Jing Bie, Lisheng Jin, and Bart van Arem, *Member, IEEE*

Abstract— **In this paper we propose a novel design for the Lane Change Assistant (LCA). For drivers on the highway, LCA advises them on whether it is safe to change lanes under the current traffic conditions. We focus on how the LCA can provide a reliable advice in practice by considering the issues of changing circumstances and measurement uncertainties. Under some generic assumptions we develop a micro-simulation model for the lane change safety assessment. The model is in line with the car following models and lane change algorithms available in literature. It retains a probabilistic character to accurately represent realistic situations. Based on a sensitivity study we are able to develop a robust design for the LCA. In this design the system accounts for the practical uncertainties by including appropriate extra safety distances. The driver interface consists of a spectrum of five LED lights, each operating on a distinct color (varying from red to green) and guaranteeing a certain safety degree. Our results allow car developers to easily acquire reliable designs for the LCA.**

I. INTRODUCTION

As a result of the enormous growth in transport in the last few decades, the road networks are getting busier and busier. To prevent dangerous situations from occurring, drivers need to pay attention to their vehicular maneuver, especially under heavy congestion. Lane changing is considered one of the most difficult tasks of driving and special attention is needed. In 2008, 1.7% of the registered highway (speed limit 100km/h and 120km/h) accidents in the Netherlands were caused by inadequate lane changing [1]. Although the percentage may not seem significant, these accidents are responsible for a considerable part of the total traffic delays [2].

One of the promising new technologies to help improve traffic safety is the Lane Change Assistant (LCA). Without LCA, drivers make lane change decisions by subjectively assessing the inter-vehicle gap and the potential hazard. It has been shown that some drivers' judgments on the lane change situation tend to be unsafe, especially at high velocities; large variation also exists in drivers' perception of inter-vehicle distances [3]. This signifies the necessity to provide drivers with information and advices on lane change. The LCA serves this very purpose. It gives an advice to the driver on whether a lane change can be safely made under the current traffic situation. Once implemented, this in-car system supports the driver during lane change maneuvers and contributes to higher safety on the roads. Consequently it also leads to a reduction in the traffic delay.

There are a few simple implementations available on lane changing safety advices. To be able to give the advice, the vehicle must be equipped with vehicle detection devices. An example of such a system is the BLind spot Information System (BLIS), developed by Volvo [4]. Small sensors are attached to the side mirrors that can detect vehicles in the blind spot. If a vehicle is detected, the driver gets a warning from the system not to change lane.

Another example is the subproject Lateral Safe in the integrated project PReVENT [5]. It aims to develop and introduce safety applications that contribute to the prevention of lateral/rear related accidents. In cooperation with the subproject MAPS & ADAS, an interface is developed which uses map data to warn the driver for upcoming dangerous situations.

The LCA addressed here is more advanced compared to BLIS and Lateral Safe. The LCA not only detects cars in the surroundings of the subject vehicle but also provides the driver with an advice. Several studies [6-9] have been performed for developing a lane change algorithm. In these studies, theoretical algorithms are proposed for determining whether it is safe to change lane or not. The prediction is based on input variables that characterize the surrounding environment in (dis-)continuous time. However, when the LCA is deployed in real life, it has to deal with several practical issues that current studies have not taken into account, such as detection errors and variability in the road/vehicle environment. To generate a reliable advice in practice, the assistant must deal with these practical issues.

In this research we analyze to what extent these issues affect the safety consequences of the LCA, and shed light on how a reliable advice for the LCA can still be drawn. We first introduce the LCA model scenario and architecture. The model setup is then described in details, followed by the

---

Manuscript received February 10, 2010.

Mark Roelofsen is with Department of Civil Engineering, Faculty of Engineering Technology, University of Twente, Drienerlolaan 5, 7522 NB Enschede, the Netherlands (e-mail: m.t.a.roelofsen@student.utwente.nl).

Jing Bie is with Centre for Transport Studies, Faculty of Engineering Technology, University of Twente, Drienerlolaan 5, 7522 NB Enschede, the Netherlands (corresponding author; phone: +31-53-489-2543, fax: +31-53-489-4040, e-mail: j.bie@utwente.nl).

Lisheng Jin is with Transportation and Traffic College, Jilin University, 5988 Renmin Street, Changchun, Jilin 130022, China (e-mail: jinls@jlu.edu.cn).

Bart van Arem is with Department of Transport and Planning, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, 2628 CN Delft, the Netherlands (e-mail: b.vanarem@tudelft.nl).

978-1-4244-7868-2/10/$26.00 ©2010 IEEE

types of uncertainties in practice. Based on the results of the sensitivity analysis, a novel LCA design is presented.

II. BACKGROUND

A. *Model Scenario*

We limit the scope of our research to the scenario in Fig. 1. The scenario consists of a one-directional highway section with two lanes and no horizontal/vertical curvature. The merging vehicle M intends to move to the left lane (e.g. to overtake the leading vehicle). The LCA equipped on M only pays attention to a maximum of four surrounding vehicles. Those vehicles are located the nearest to M:

L_o is the leading vehicle in the original lane;
L_d is the leading vehicle in the destination lane;
F_o is the following vehicle in the original lane;
F_d is the following vehicle in the destination lane.

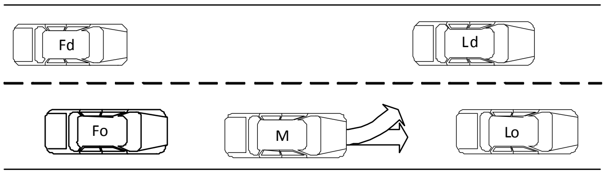

Fig. 1. Model scenario: configuration of initial vehicle position.

The LCA uses detection technologies and does not require communication with other vehicles (V2V) or the infrastructure (V2I). We only consider lane changes with the left lane as destination lane (Fig. 1). Lane changes to the right lane can be analyzed in a symmetric way.

B. *LCA Architecture*

Fig. 2 depicts the general architecture of a lateral driver support system [10]. In this research we focus on the safety assessment algorithm, under the sub-function "Think." This is the step where the LCA generates an advice by applying an assessment algorithm. The sensors in sub-function "Sense" provide the inputs, while the human machine interface (HMI) in sub-function "Act" communicates the output (i.e. advice) to the driver.

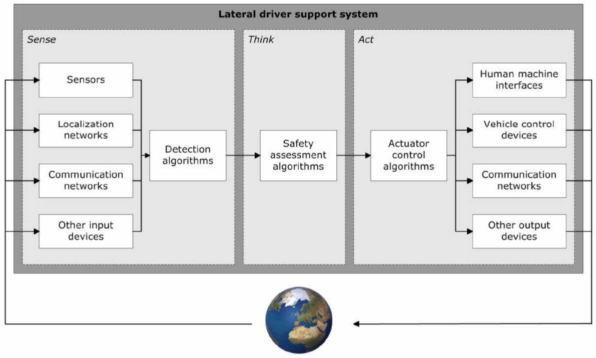

Fig. 2. Architecture of a lateral driver support system [10].

Different designs of the LCA changes the way it functions [10]. Within this research the LCA advices in a positive way. This means that it informs the driver on how safe it is to make a lane change, in contrast to a negative type where the level of danger (or "unsafety") is communicated. The LCA assists the driver by way of informing rather than taking over tasks. It does not intervene with the driver's control of the vehicle. In this way the driver stays "in the loop" and remains responsible for controlling the vehicle.

We restrict our consideration to the free lane-changing scenario, thus not during merging from a ramp or an emergency lane change. A survey among drivers concludes that 94% of the drivers think an assistant can be useful in a free lane-changing scenario [11]. The HMI consists of five LED lights, each operating on a distinct color and representing a certain safety level. In this way the LCA can generate a series of advices based on the probabilistic nature of safety guarantee, rather than a simplistic yes/no answer on the safety level. Without a 100% safety guarantee, the driver once more stays in the loop and remains responsible.

III. MODEL SETUP

We adopt the lane change model of [7] as a basis. This model enables us to implement and expand the algorithm and to reduce the number of assumptions. Moreover, it has a relatively low amount of measured variables and several static variables, which improves the robustness of the LCA.

To create a complete traffic model, this lane change model is combined with a vehicle following model. Several input variables, including initial vehicle locations, speeds and acceleration rates, are adjustable in order to create specific traffic situations. The software MATLAB is used as the simulation environment. The output is visualized by bird's-eye (or aerial) view of the highway, where the vehicle movements are illustrated through a series of "snapshots".

A. *The Combined Model*

The model incorporates all different situations that can occur when drivers perform the lane change. Chronologically, these typical situations are: (1) M is cruising unhindered in the original lane. (2) M decelerates when it approaches the preceding vehicle L_o. (3) M intends a lane change and accelerates again. (4) M decelerates in the target lane when it approaches the preceding vehicle L_d. (5) When there is a sufficient headway, M accelerates to its preferred speed. When mirrored, these interactions also apply between vehicle M and the following vehicles, F_o and F_d.

To simulate these situations, the model includes several sub-models: positioning, acceleration, lane change, and brake. The positioning sub-model calculates the longitudinal and lateral positions of each vehicle for every time step Δt. The acceleration sub-model enables the subject vehicle to accelerate to its preferred speed. The lane change sub-model, when needed, determines whether it is safe to change lane under the current situation. Finally, the brake sub-model makes sure that vehicles start decelerating in time, in order to maintain a safe longitudinal gap of at least two seconds [12] with their predecessors.

In order to guarantee safety, certain hierarchy (Fig. 3) is applied in these sub-models. First, the braking sub-model overrules the acceleration and lane change sub-models. Secondly, the acceleration sub-model overrules the lane change sub-model. Drivers prefer to stay in the current lane, until the position of the preceding vehicle does not allow the preferred speed anymore. Then the lane change sub-model is initiated and a lane change, if safe, takes place.

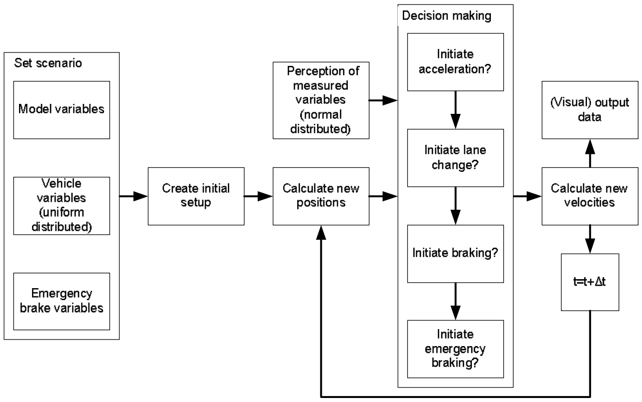

Fig. 3. The combined model in the MATLAB simulation.

B. The Lane Change Model

When a lane change is desired, the lane change sub-model calculates whether it is safe to perform such an action. Here we distinguish practical safety from theoretical safety. A car following situation is theoretically safe if by performing an emergency brake, the stopping distance between the leading and following vehicles is larger than zero. In practice, we need to consider certain safety margins, i.e. an extra safety distance above the regular minimal longitudinal distance. If this extra safety distance is guaranteed between M and both vehicles in the destination lane (i.e. L_d and F_d) then the simulation model deems it safe to change lane.

In this study we adopt the lane change model of [7], where this extra safety distance is calculated as:

$$D_{cr}(t) = c_1 \cdot v_{following}(t) + D_0. \tag{1}$$

Here $D_{cr}(t)$ defines the critical following distance at time t. Velocity of the following vehicle is given by $v_{following}(t)$. Parameter c_1 is a pre-determined time headway (the *critical headway*, usually 1~2s in practice) and D_0 is the minimum stopping distance.

C. The MATLAB Simulation

In the MATLAB simulation, the sub-models are iterated per time interval (Δt, set as 0.1s here). One simulation run lasts 20 seconds, and the time period that M needs to complete a lateral displacement during lane change is set to be 5s. For each simulation, 1000 runs are executed with a random configuration of the variables. Each adjustable input variable is randomly generated from a predefined uniform distribution. The range of the distribution is set in a way that provokes critical lane change situations while maintaining a safe starting position. By repeating these random runs, we can simulate all situations within the predefined scenario. Fig. 4 gives an example of the initial vehicle positions as well as the dimensions of a random run.

Time to collision (TTC) is often used as the key safety indicator, as it takes both distance and relative velocity into account [13]. For simplicity reasons, however, this research uses the ratio of critical situations as a safety measure. A critical situation occurs when the gap between M and any of the surrounding vehicles falls shorter than 0.5s. Similar to TTC, this measure takes both distance and relative velocity into account. The key performance indicator of the lane change model is then given by the *safety degree* (or *safety ratio*), defined as

$$\text{safety deg.} = \frac{\text{\# runs without critical situation}}{\text{total \# runs}} \times 100\%. \tag{2}$$

IV. ELEMENTS OF UNCERTAINTY

The goal of this research is to find out how the LCA can be implemented in practice. In reality, the LCA has to deal with several practical issues. These issues may have negative impacts on the reliability of the output. An incorrect advice from the LCA can directly lead to dangerous situations. To calculate the appropriate safety margins for a desired level of reliability, first we have to quantify the consequences of those practical issues. In this study we consider the following uncertainties: those resulting from changing circumstances, and those from measurement inaccuracy.

A. Changing Circumstances

The LCA has to make a prediction for the traffic situation during the next few seconds. Since traffic can be very dynamic, predicting a traffic situation a few seconds ahead gives a certain degree of uncertainty in practice. The LCA has to consider possible changes in the circumstances and take into account the influence of an unexpected event.

In this study we specifically consider the scenario of an

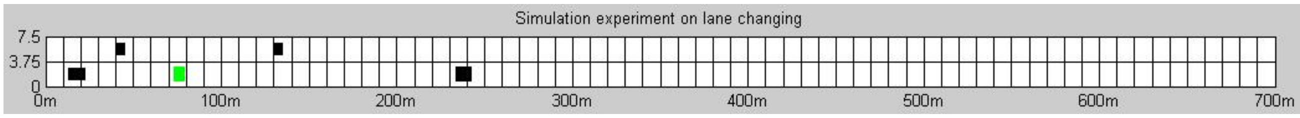

Fig. 4. Random initial vehicle positions and dimensions (subject vehicle depicted in green).

emergency brake by the preceding vehicle. This can have a major impact on the LCA reliability. The LCA has to be designed in a way that is robust enough to handle this situation. For the simulation in MATLAB, within the first 8s of each run, one of the leading vehicles is set to suddenly start an emergency brake.

Research has been done on two important aspects that affect the consequences of an emergency brake, namely the road conditions and reaction time [14]. Other factors that can lead to unexpected changing circumstances, such as road curvature and vibrations, are assumed to have less severe impact than an emergency brake scenario.

B. *Measurement Uncertainties*

The LCA relies on certain inputs in order to generate an advice for the driver. Sensing devices are equipped on the subject vehicle to detect the environment and obtain the necessary information. In practice, normally there are errors in these inputs or even missing data, due to the imperfect detection technologies. Therefore the LCA has to deal with measurement uncertainties in the inputs.

To analyze the impact of these errors in the input variables, we first classify the sensitivity of each variable and the degree of measurement uncertainty. In total there are seven variables that are measured continuously and may contain a measurement error: the velocity of M, F_d and L_d; the longitudinal position of M, F_d and L_d; and, the length of vehicle L_d. Uncertainty about lateral displacement is not considered in this research.

We simulate the case by randomizing the input variables in the model. We know precisely the real values of the variables. The input variables for the LCA are, however, normally distributed random variables. They have their mean values equal to the real values, while the standard deviations (s.d.) are preset. This modification makes the simulation runs probabilistic instead of deterministic.

V. SENSITIVITY ANALYSIS

Sensitivity analyses are performed for the two factors in changing circumstances (road condition and reaction time) and the seven variables in measurement uncertainties. For each variable, we adopt a series of different values and calculate the corresponding safety degrees, while keeping the other variables constant. Here we apply the values c_1=1.5s and D_0=10m for the lane change model.

A. *Changing Circumstances*

Fig. 5-6 depict the sensitivity of safety degrees on road conditions and reaction time. The road condition parameter σ has a range of 0 (dry asphalt) to 1.2 (rainy) [14]. Fig. 5 shows that when σ is small, the safety degrees are almost unaffected by the varying values of σ. However, for large σ's, the value of σ has a significant impact on the safety degrees. In Fig. 6, there is a linear correlation between the safety degrees and the reaction time, indicating a significant impact of the latter.

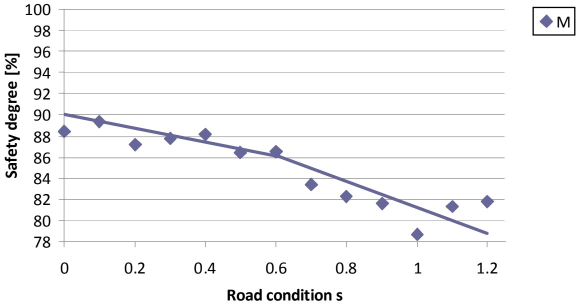

Fig. 5. Sensitivity on road conditions.

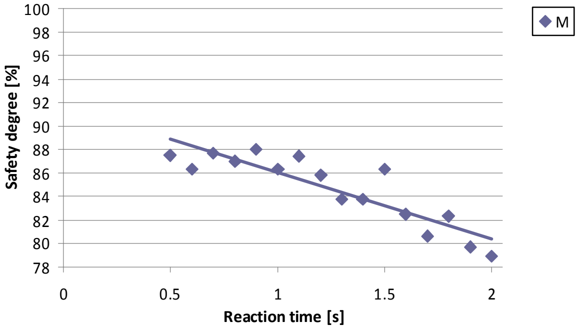

Fig. 6. Sensitivity on reaction time.

These figures suggest that both road conditions and reaction time have noteworthy consequences on the safety degree. To be able to give reliable advices, the LCA needs to take both issues into account.

B. *Measurement Uncertainty*

Seven variables are examined: the positions of M, F_d and L_d, the velocities of M, F_d and L_d, and the length of vehicle L_d. Fig. 7-9 depict the sensitivity of safety degrees on the different standard deviations of these variables. In Fig. 7 we see that accuracy in the vehicle positions has a minimal impact on the safety degrees, especially for low values of s.d. where the curves are almost horizontal. Fig. 8 also shows insignificant impacts. Safety degree is almost independent of the measurement accuracy in L_d's speed. There is a somewhat linear relationship between the safety degree and the s.d. of F_d's speed; this also holds for M when the values of s.d. are low. In Fig. 9, again the safety degree is not very much affected by the length of L_d.

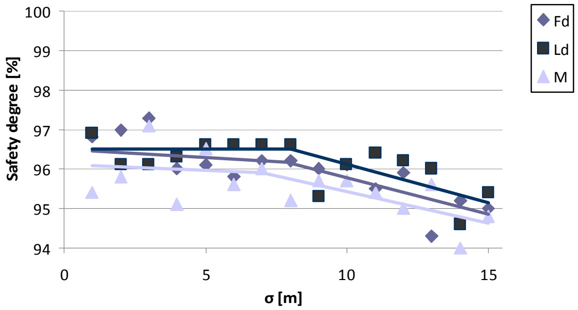

Fig. 7. Sensitivity on vehicle positions.

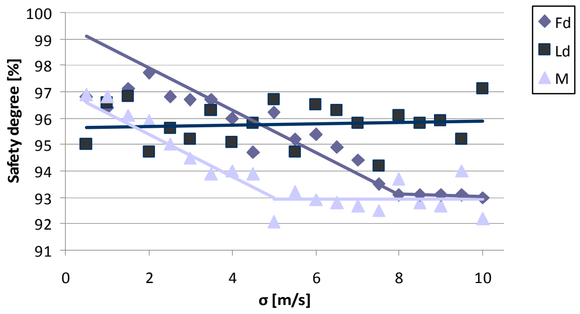

Fig. 8. Sensitivity on vehicle speeds.

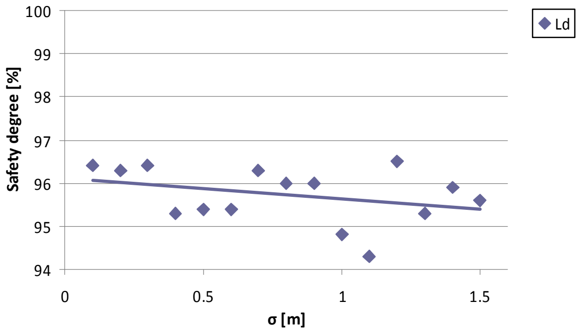

Fig. 9. Sensitivity on vehicle length.

Compared to road conditions and reaction time, the consequences of measurement uncertainties are relatively low. The sensitivity of the safety degree on these issues is also low. Moreover, state of the art detection devices often use sophisticated techniques; this results in an even lower uncertainty level (s.d.). Despite the limited impact of input uncertainties on the safety level, we will still consider these variables in our LCA design, in order to best adapt it to the environment in practice.

VI. AN INNOVATIVE DESIGN FOR THE LCA

A. *Design based on Safety Levels*

The previous section shows that the safety degree is dependent on road condition and reaction time (with significant impacts), as well as precision in the seven measurement variables (with less significant impacts). Furthermore, it should be noted that the safety degree is closely related to the extra safety distance in Eq. (1).

To achieve various safety levels under a particular situation, the proposed LCA design uses an HMI with a spectrum of five LED lights, each of a distinct color and representing a different safety level. The safety levels can be chosen by the system developer. First the developer selects the worst-case scenario that the LCA should be able to handle. There are nine variables that have an influence on the reliability of the LCA advice: two variables related to the emergency brake scenario (road conditions, reaction time) and seven variables on measurement uncertainties. Once the worst-case scenario has been defined by setting these variables (or calibrating them from field data), the developer can assign a safety degree to every safety level. Each safety degree corresponds to a certain value of c_1, and thus a certain safety distance.

B. *Illustration*

Here we illustrate how to apply the method on a certain scenario. To be able to give advices on a spectrum of five safety levels, we should first specify these levels by using different values for safety parameter c_1. For example we choose the worst-case scenario as rainy weather conditions where the nine variables are set as in Table 1:

TABLE 1
VARIABLES IN THE SELECTED SCENARIO

Variable	Value
Road condition	1.2 (rain)
Reaction time	1.5s
Velocity vehicle M	σ = 5m/s
Velocity vehicle F_d	σ = 5m/s
Velocity vehicle L_d	σ = 5m/s
Length vehicle L_d	σ = 1m
Position vehicle M	σ = 8m
Position vehicle F_d	σ = 8m
Position vehicle L_d	σ = 8m

Fig. 10 shows the relationship between c_1 and the safety degree under the selected scenario. Here we assume that a safety level below 70% is unacceptable. Furthermore, the optimal safety level is the maximum value of the trend line: 84.4%. For these safety levels, the corresponding values for c_1 are 0.03s and 2.23s, respectively.

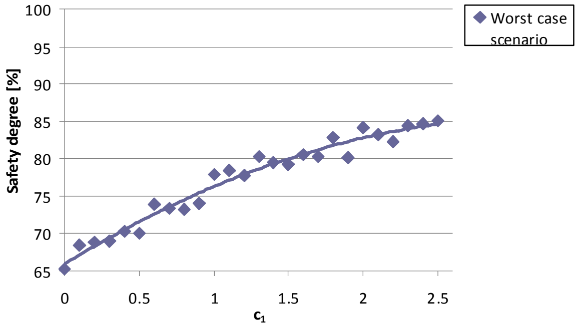

Fig. 10. Safety level in the emergency scenario.

Although the curve in Fig. 10 is not linear, for simplicity the safety levels are still set with equal steps of 0.55s for c_1. Table 2 provides an overview on the corresponding safety values under this emergency brake scenario. In addition, Table 2 also includes the corresponding safety degrees under a normal scenario, which gives a better representation on how good the LCA performance would be in practice.

TABLE 2
OVERVIEW OF DIFFERENT SAFETY LEVELS IN THE LCA DESIGN

HMI (the burning LED)	1	2	3	4	5
Safety parameter c_1 (s)	0.03	0.58	1.13	1.68	2.23
Safety degree under emergency brake scenario (%)	70.0	76.3	80.8	83.5	84.4
Safety degree under normal scenario (%)	67.3	80.7	90.6	97.0	99.8

By using the results in Table 2, it is possible to define the collision regions. The simulation model of the LCA takes vehicles L_d and F_d into account when generating an advice. For both vehicles, the MATLAB simulation is used to define the safe and unsafe regions. We plot the five different safety levels of the LCA by setting out the relative velocity against the minimal required gap. Fig. 11-12 depict the safe and unsafe regions for the scenario described in Table 1.

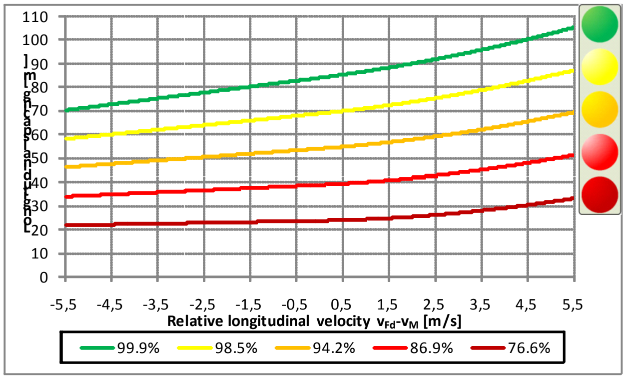

Fig. 11. The collision region between M and F_d.

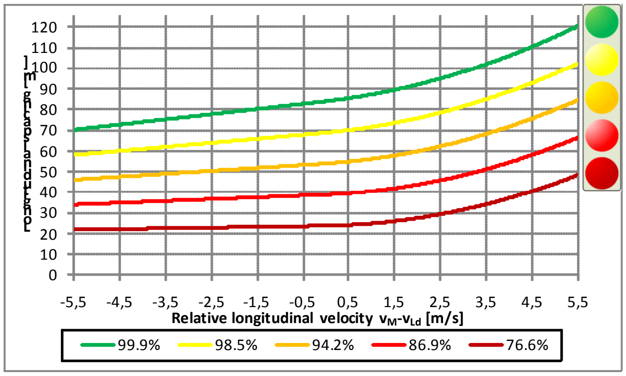

Fig. 12. The collision region between M and L_d.

In calculating a safety advice, the LCA should consider the safety distance of M from both F_d and L_d. These two figures give clear quantification on what safety distance is needed to guarantee a certain safety level. As shown in the figures, the safety levels are directly linked with the HMI. For example, for the case where the relative velocity between F_d and M is +3.5 (Fig. 11), the first LED light starts burning at a gap of 28m, guaranteeing 67.3% safety, and the fifth LED starts burning at a gap of 96m, guaranteeing 99.8% safety.

The difference between Fig. 11 and Fig. 12 signifies that, under positive values of the relative longitudinal velocity, vehicle M requires more safety spacing with L_d than F_d. This is reasonable as M needs to accelerate when initiating a lane change.

VII. CONCLUSIONS

In this paper we propose a novel design for the LCA. The LCA continuously calculates the safety distances for five different safety levels. The configuration of these safety levels depends on the worst-case scenario that the LCA is supposed to handle. This configuration can be set up by specifying the nine variables related to the practical issues (changing circumstances and measurement uncertainties). A tradeoff has to be made between safety and usability, since high safety guarantee leads to long safety distances.

The HMI of the LCA consists of five LED lights. When the LCA gives a positive advice at the lowest safety level, only the red LED will be turned on. A positive advice at the maximum safety level makes the top LED (green) on. Thus, a positive advice for the selected scenario guarantees certain minimum and maximum safety level. Finally, the driver remains responsible for his decision on whether to change lane or not.

The LCA in this study is not linked with other driver assistance systems. Future systems can connect the LCA with for instance a rain detector, which informs the LCA about the current weather conditions. The LCA can then choose a setting most suited for the current environment. This makes the LCA advices more reliable and more useful. Similar cooperative advantages can also be achieved with other ITS systems and services.

REFERENCES

[1] SWOV. Accidents, drivers and victims in the Netherlands. Available: http://www.swov.nl

[2] H. Jula, E. B. Kosmatopoulos, and P. A. Ioannou, "Collision avoidance analysis for lane changing and merging," *IEEE Transactions on Vehicular Technology*, vol. 49 (6), pp. 2295-2308, Nov. 2000.

[3] M. Hashimoto, T. Suetomi, A. Okuno, and H. Uemura, "A study on driver model for lane change judgement," *JSAE Review*, Vol. 22 (2), pp. 183-188, Apr. 2001.

[4] M. Hanlon. (2004, August 04). *Volvo Launches Blind Spot Information System (BLIS)*. Available: http://www.gizmag.com/go/2937/

[5] PReVENT. *Lateral Safe*. Available: http://www.prevent-ip.org

[6] L. Bascunana, "Analysis of lane change crash avoidance," *SAE Technical Paper Series 951895*, pp. 33-41, Aug. 1995.

[7] L. S. Jin, W. P. Fang, Y. N. Zhang, S. B. Yang, and H. J. Hou, "Research on safety lane change model of driver assistant system on highway," in *Proc. 2009 IEEE Intelligent Vehicles Symposium,* pp. 1051-1056.

[8] A. Kanaris, E. B. Kosmatopoulos, and P. A. Ioannou, "Strategies and spacing requirements for lane changing and merging in automated highway systems," *IEEE Transactions on Vehicular Technology*, vol. 50 (6), pp. 1568-1581, Nov. 2001.

[9] C. Hatipoglu, U. Ozguner, and K. A. Redmill, "Automated lane change controller design," *IEEE Transactions on Intelligent Transportation Systems*, Vol. 4 (1), pp. 13- 22, Mar. 2003.

[10] M. Tideman, M. C. van der Voort, B. van Arem, and F. Tillema, "A review of lateral driver support systems," in *Proc. 2007 IEEE Intelligent Transport Systems Conference (ITSC)*, pp. 992-999.

[11] T. van Dijck and G. A. J. van der Heijden, "VisionSense: an advanced lateral collision warning system," in *Proc. 2005 IEEE Intelligent Vehicles Symposium*, pp. 296-301.

[12] Dutch Ministry of Transport, Public Works and Water Management. *Houd 2 seconden afstand* (Keep 2 seconds' distance). Available: http://www.verkeerenwaterstaat.nl

[13] S. E. Lee, E. C. B. Olsen, and W. W. Wierwille, "A comprehensive examination of naturalistic lane changes," NHTSA, Report No. DOT-HS-809-702, Mar. 2004.

[14] M. Y. Bian, K. Q. Li, D. F. Jin, and X. M. Lian, "A velocity control strategy for vehicular collision avoidance system," in *Proc. 2005 IEEE International Conference on Mechatronics and Automation*, Vol. 4, pp. 1827-1830.