V2V-Based Vehicle Risk Assessment and Control for Lane-Keeping and Collision Avoidance

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***Abstract*—This article analyzes a typical numerical method to deal with maintaining vehicle's track for self-governed (autonomous) driving and obstacle avoidance. The new approach utilizes the established cost function definition consolidating the basic aspect of the dynamic conditions of the vehicle as position, orientation, and maximum allowed speed on road. The optimization processes minimize the cost function while determining the ideal track by fluctuating steering-angle and braking-ratio amplitudes. Vehicle-to-vehicle (V2V) communication framework is viably used through providing data on maximal road speed and road's obstacle dimensions. The parametric definition of obstacles creates an adaptable domain for low and high-speed simulations. The minimal number of influential optimization variables ensures a steady and direct generation of ideal results. By the current novel approach, we are independently able to move the vehicle on an arbitrary track approximated by low-order polynomials. Simulation tests are performed under vehicle's speeds of 10m/s, 18 m/s whilst utilizing most important features of Vehicle-to-vehicle communication systems.**

***Index Terms*—lane-keeping, collision-avoidance, automotive, autonomous vehicle, model predictive control, Vehicle-to-Vehicle (V2V), risk assessment, control**

I. INTRODUCTION

Recently in 2016, the World Health Organization (WHO) has stated a key fact that 1.25 million people die each year as a result of road traffic crashes [1]. The European Road Safety Observatory estimated in their annual report [2] in 2008 that 43,000 fatalities and 1.8 million injuries are caused by road accidents each year within the European Union only. Previous study [3] showed that unintentional lane departure accidents were accounted for 14% of all accidents reported in Germany only which also caused 30% of all road accidents fatalities in the year 2013. Moreover, a research has predicted that road traffic accidents will increase globally by 67% by the year 2020 [4].

The threat assessment block of Active Safety systems is accountable for collecting the environment information by means of sensors fusion technique after applying mathematical modeling for estimating the risk likelihood [5]. A method that studied certain systems concerning decision-making blocks was presented in [6] as Neural Networks and in [7] as Model Predictive Control. Integration of Vehicle-to-Vehicle (V2V) systems allow the control model inside an automobile to stay aware of surrounding environment situations within a discrete abstracted fashion. The importance of including Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication systems on the road is broadly discussed in the surveys carried out in [8].

This paper is objected towards developing a risk-assessment algorithm that could control a vehicle to keep the presented lane and avoid a collision that may be caused by a road object. The algorithm is designed in a way that deals with the provided optimization problem in a complete symbolic numerical behavior. Some effective parameters are treated as a given input from an integrated Vehicle-to-Vehicle (V2V) or Vehicle-to-Anydevice (V2X) systems, such as road's obstacle dimensions and information on road's velocity. The paper discusses a fully numerical approach through modeling, simulation, and integration of novel V2V methods.

The rest of this paper is organized as follows; In Section 2 the vehicle's dynamics and equations of motion that represent vehicle's behavior in addition to the road model along with the mathematical behavior of the control algorithm. Section 3 presents validation results under different scenarios. Section 4 concludes and discusses the work and proposed future work.

II. MODELING

In this section, the defining model equations used by the optimization and control algorithm is presented. Section 2-A introduces the used vehicle mathematical model in the work, Section 2-B introduces the modeled road geometry, and

Section 2-C introduces the proposed optimization and control algorithm for lane keeping and collision avoidance combined.

A. Vehicle Model

For this study, a four-wheel vehicle model is adapted from the work [7] which allows controlling and simulating the vehicle's dynamics due to the degrees-of-freedom of this model.

The following set of 2^{nd} order differential equations for the variables x, y, ψ are used to describe vehicle motion

$$m\ddot{x} = m\dot{y}\dot{\psi} + \sum_{i=1}^{4} F_{xi} \tag{1}$$

$$m\ddot{y} = -m\dot{x}\dot{\psi} + \sum_{i=1}^{4} F_{yi} \tag{2}$$

$$\begin{aligned} J_z\ddot{\psi} = l_f(F_{y1} + F_{y2}) - l_r(F_{y3} + F_{y4}) + \\ \frac{w_t}{2}(-F_{x1} + F_{x2} - F_{x3} + F_{x4}) \end{aligned} \tag{3}$$

where x, y and ψ are the longitudinal, lateral and turning positions of the vehicle respectively. l_f and l_r are the lengths of front and rear vehicle axles, w_t is the width of the vehicle, J_z is the vehicle yaw inertia, F_{xi} and F_{yi}, for $i \in \{1, 2, 3, 4\}$, are the longitudinal and lateral tire force components in the vehicle body frame for each tire and they are modeled as

$$F_{xi} = f_{xi}\cos(\delta_i) - f_{yi}\sin(\delta_i) \tag{4}$$

$$F_{yi} = f_{xi}\sin(\delta_i) + f_{yi}\cos(\delta_i) \tag{5}$$

where δ_i is the steering angle corresponding to wheel $i \in \{1, 2, 3, 4\}$ and f_{xi} is the longitudinal tire force in the tire frame which is computed in the following way:

$$f_{xi} = \beta_r \mu_i F_{zi} \tag{6}$$

where F_{zi} is the vertical tire force in vehicle frame for every tire - or the vertical load of every tire, and $\beta_r \in [-1, 1]$ is referred to as the braking ratio. $\beta_r = -1$ corresponds to full braking while $\beta_r = 1$ corresponds to full throttle. Braking and throttle are taken into consideration as accelerating and decelerating so that the velocity will never be constant while $\beta_r \neq 0$.

The lateral tire force in the tire frame is computed using a modified nonlinear Fiala tire model [9] which is assumed to be later replaced by anti-lock braking, and traction control systems as mentioned in [10]. In which case, the lateral tire force will be treated as an output of these systems to our presented optimization and control algorithm.

B. Road Geometry Model

In this section, road modeling is performed using mathematical interpolation of road-line sections. In case of obstacle-avoidance scheme, an interpolation of a higher order polynomial function is performed. The interpolated object-curve is constructed using the dimensions of the obstacle being detected by means of V2V communications. 2^{nd} order polynomial function is used if there is no objects to avoid, where then the obstacle's dimensions parameters are set to zero. Listed below are the types of road models which have been designed in the course of the simulation process

1) Lane-Keeping Road Geometry: This geometry is described using a 2^{nd} order polynomial equation as follows,

$$F_{road}(x) = kx^2 + m \tag{7}$$

where k and m are parameters that define the slope of the road in addition to the steepness and elevation, while x is the longitudinal position of the vehicle. The geometry was formulated to be x-dependent instead of being time-dependent so that the road curvature is aligned with the x, y coordinates graphing of the vehicle. A feature is added to the geometry in order to create a collision avoidance curve that will be discussed later in this section.

2) Collision-Avoidance Road Geometry: The data of the obstacle is assumed to be available using V2V communication systems as mentioned in [11]. The obstacle geometry is currently a rectangular box with width and depth, where width is denoted as final-initial coordinates, while depth is denoted as ϵ. At the case where $\epsilon 0$, the interpolation will fail and the road geometry is transformed to be a normal line-keeping path not a collision-avoidance path.

The flexible approach of *Mathematica* was used to apply the most suitable technique for interpolation according to the nature of the curved road. The available techniques switches between the Spline and Hermite techniques in an automatic way.

C. Optimization and Control Algorithm

The optimization parameters which govern and affect the objective function are discussed. Moreover, the constraints and penalty function that outline the association among the violation of the constraints and the objective function are additionally mentioned in detail in this sub-section.

1) Objective Function: The formulated problem has an objective function C to be met with a minimum cost while having constraints that should not be violated. The optimization problem has two varying field-of-search parameters, (δ, β), while five constraints to be fulfilled. Two of these parameters describe the vehicle's behavior; i.e. steering angle δ and braking ratio β. Penalization is a well known technique in optimization that offers the benefit of convexity of the problem. Other beneficial features of penalization is having differential values of cost so that search time for a minimum cost is minimized.

To generate a flexible way to optimize the driving process penalty weights p_i, $i = 1, 2, \ldots, 4$ shall be used for the different components of the cost function. The penalty weights are determined according to the importance and major contribution to the cost function. The values are fixed experimentally and allow a broad variation of the optimization process. The cost function uses the method of a least square optimization where different components contribute to the cost function. The following formula comprehends these components:

$$C(\delta, \beta) = \sum_{i=1}^{4} p_i \xi_i^2 \tag{8}$$

subject to the constraints $\delta_{\min} \leq \delta \leq \delta_{\max}$, $\beta_{\min} \leq \beta \leq \beta_{\max}$. The cost function components ξ_i are measuring the deviation from a predefined target value as:

$$\xi_i = \xi_i^t - \Xi_i \text{ with } \; i = 1, 2, \ldots, 4\,. \tag{9}$$

The values ξ_i^t are known quantities and shall be fixed in the cost function. As mentioned the p_i are the penalty weights of the cost function and are also known in the optimization. The ideal line is the reference system to which the dynamical quantities like position, orientation, and velocity are adapted.

As mentioned the first cost component Ξ_1 is assigned to the line element Δs. The line element Δs measures the deviation of the position of the car to the ideal position at the current time. Thus, the deviation is determined by the x and y coordinates of the vehicle $(x(t), y(t))$ and the ideal line coordinates (x_l, y_l). The line element is then:

$$\Xi_1^2 = \Delta \mathrm{s}^2 = \Delta \mathrm{x}^2 + \Delta \mathrm{y}^2 = (x_l - x(t))^2 + (y_l - y(t))^2 \tag{10}$$

The optimal solution of the location is reached if $\Delta \mathrm{s}^2 = 0$ when the vehicle is located on the ideal line. In addition to the location the vehicle has a certain orientation with respect to the ideal line. The direction of the car is determined by the velocity $\vec{v}$ with its magnitude $v = \left\|\vec{v}\right\|$ and its direction as a vector $\vec{v} = (\dot{x}(t), \dot{y}(t))$. If the current location of the car is used to determine the tangent vector $\vec{t}$ to the ideal line there is a complete orientation of the two vectors $\vec{t}$ and $\vec{v}$ are parallel. This means that according to the relation

$$\vec{t}\,.\vec{v} = \left\|\vec{t}\right\| \left\|\vec{v}\right\| \cos(\theta) \tag{11}$$

we are able to determine the deviation of the orientation as

$$\cos(\theta) = \frac{\vec{t}\,.\vec{v}}{\left\|\vec{t}\right\| \left\|\vec{v}\right\|}, \tag{12}$$

where θ is the alignment angle between the two vectors $\vec{v}$ and $\vec{t}$. From relation (12) it is obvious that the normalized dot product is limited to a finite range $[-1, 1]$. The center of this range is known to be related to the orthogonality of the two vectors which is not the target of the optimization. The alignment or anti-alignment of the vectors is given by the end values of the interval.

The second component Ξ_2 is given by

$$\Xi_2 = \cos(\theta)^2 = \left(\frac{\vec{t}\,.\vec{v}}{\left\|\vec{t}\right\| \left\|\vec{v}\right\|}\right)^2, \tag{13}$$

using the target value $\xi_2^t = 1$ corresponding to an angle $\theta = 0$ or multiples of π. The even multiples are related to the alignment while the odd multiples of π are anti-alignments.

By introducing this component into the optimization a state where the vehicle was kept on track could be reached. However, if a search for an optimal solution under these conditions was done, it was found that the constrained variation of the braking ration β is not sufficient for the stable operation of the vehicle. It turned out that including the constrained on β as:

$$\beta_{\min} \leq \beta \leq \beta_{\max} \tag{14}$$

is not stabilizing the dynamic behavior of the car. The minimal and maximal values of β are according to their theoretical definitions given by $\beta_{\min} = -1$, and $\beta_{\max} = 1$ corresponding to deceleration and acceleration of the vehicle respectively. However, the examination of the dynamical equations previously mentioned demonstrate that the limiting theoretical values are not allowed due to the generation of singularities in the model.

The observation also was that the velocity in some cases continuously increased which results to an off-road situation. Therefore it was decided in view of the obstacle-avoidance conditions to limit the velocity to a given constant maximal value. In lane-keeping conditions, the maximal velocity value is adapted from the work in [11] by requesting a collective information of obstacle or road's maximum velocity when requested based on established V2V communication systems. The vehicle's velocity limitation is incorporated by defining

$$\Xi_3 = \sqrt{\dot{x}^2 + \dot{y}^2} = v \tag{15}$$

and limit the velocity by the target value $\xi_3^t = v_{\max}$.

Including all the components discussed above and adding the constraints the optimization problem has the following specific representation:

$$\begin{aligned} C(\delta, \beta) &= \sum_{i=1}^{4} p_i \xi_i^2 \\ &= \sum_{i=1}^{4} p_i \left(\xi_i^t - \Xi_i\right)^2 \\ &= p_1 \left((x_l - x(t))^2 + (y_l - y(t))^2\right)^2 + \\ & \quad p_2 \left(1 - \left(\frac{\vec{t}\,.\vec{v}}{\left\|\vec{t}\right\| \left\|\vec{v}\right\|}\right)^2\right)^2 + \\ & \quad p_3 \left(v_{\max} - \sqrt{\dot{x}^2 + \dot{y}^2}\right)^2 \end{aligned} \tag{16}$$

subject to $\delta_{\text{min}} \leq \delta \leq \delta_{\text{max}}$, $\beta_{\text{min}} \leq \beta \leq \beta_{\text{max}}$.

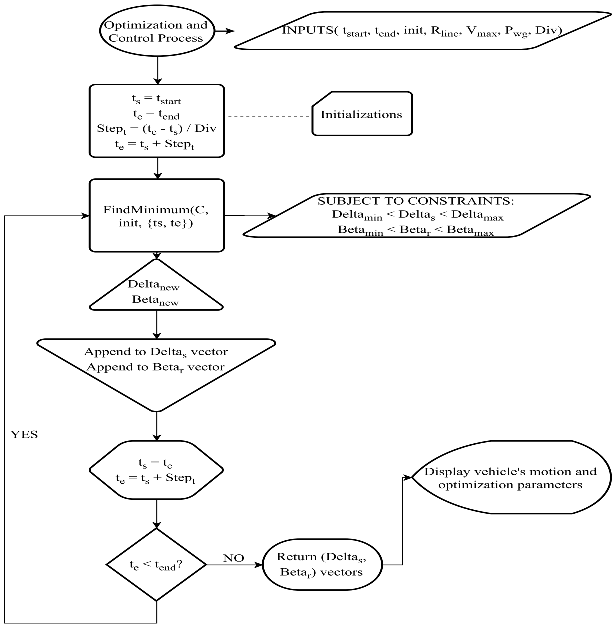

Fig. 1. Optimization algorithm for collecting the data of each iteration and interpolate it into a vector that can be visualized after the process is done.

The proposed optimization and control algorithm is shown in Fig. 1 where t_{start} and t_{end} are the limits of the whole simulation interval, t_s and t_e are the limits of each optimization iteration based on the discrete sampling. $Delta_{new}$ and $Beta_{new}$ are the new optimized steering angle and braking ratio for the current iteration that corresponds to a minimum C which is the cost function. $init$ are the initial values for x, $\dot{x}$, y, $\dot{y}$, ψ, and $\dot{\psi}$. Div denotes the number of divisions that the whole interval should be sampled to. R_{line} denotes the ideal line that the optimization should refer to when calculating the minimum cost function. V_{max} and P_{wg} denotes the maximum allowed velocity and constraints violation penalty weights respectively.

III. Results

The vehicle parameters chosen for the test and validation are shown in Table I. The parameters are used in order to simulate the reaction of a real vehicle in the simulation carried out through this work. These parameter represent the dimensions and forces of a commercial vehicle.

1) Maintaining a parabolic road at a velocity 18 m/s: A tested scenario for the vehicle at an initial velocity of 18 m/s was done using a road model of a parabolic surface. The goal of the control algorithm is to maintain the ideal road and keeping cost function at minimal value. The optimization and design parameters chosen for this test are shown in Table II.

It is observed in Fig. 2, which indicates the vehicle's performance, that the control algorithm could efficiently maintain the automobile close to the best road geometry together with a minimal error without exceeding presented lane safe margins whilst keeping road's velocity limits. Fig. 3, which shows the cost function value all through the simulation, indicates that the optimization was successful at keeping the vehicle positions within the safe limits of the ideal road to-follow.

TABLE I
VEHICLE PARAMETERS

Parameter	Value	Units
w_t	1.63	m
l_f	1.43	m
l_r	1.47	m
μ	1	-
C_α	$80,000$	-
m	2050	kg
$Fz_{1,2}$	$26,719$	N
$Fz_{3,4}$	$21,295$	N
J_z	3344	$kg.m^2$

TABLE II
OPTIMIZATION PARAMETERS FOR 18M/S VELOCITY SCENARIO

Parameter	Value	Units	Parameter	Value	Units
x	0.01	m	$\dot{x}$	18	$\frac{m}{s}$
y	0.1	m	$\dot{y}$	0.5	$\frac{m}{s}$
N_d	250	—	v_{max}	2.5	$\frac{m}{s}$
p_1	0.45	—	p_2	0.45	—
p_3	0.1	—	p_4	1	—
ϵ	0.7	m	t_{sim}	2	sec

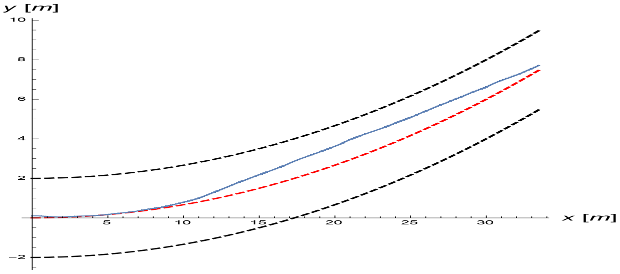

Fig. 2. The parametric plot result on vehicle positions is done through the optimization and control algorithm at an initial input velocity of 18 m/s. The centered red dashed plot represents the ideal road whilst the sided black dashed plots characterize left and right lane margin.

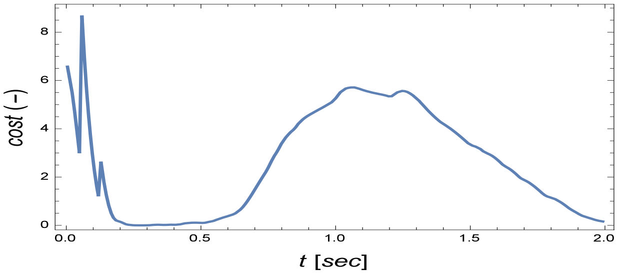

Fig. 3. The plot indicates the change of the cost function for the duration of the process.

2) Approaching an obstacle at velocity of 10 m/s: The optimization and control algorithm is tested by observing the vehicle's performance towards following the ideal path and avoiding the presented obstacle. The optimization and design parameters chosen for this test case are shown in Table III.

TABLE III
OPTIMIZATION PARAMETERS FOR 10M/S VELOCITY AT AN OBSTACLE SCENARIO

Parameter	Value	Units	Parameter	Value	Units
x	0.01	m	$\dot{x}$	10	$\frac{m}{s}$
y	0	m	$\dot{y}$	1	$\frac{m}{s}$
N_d	50	$-$	v_{max}	9.5	$\frac{m}{s}$
p_1	0.75	$-$	p_2	0.45	$-$
p_3	0.1	$-$	p_4	0.1	$-$
ϵ	0	m	t_{sim}	2	sec

Shown in Fig. 4 is the vehicle performance on the road model presented and the relative cost function plot during the control process. The road geometry presented for this scenario's evaluation test, as discussed in Section II. B., has a parabolic geometry with a presented obstacle which is required to be avoided by the optimization and control algorithm.

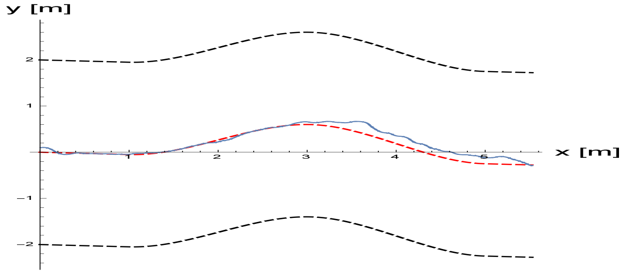

Fig. 4. The parametric plot result of vehicle positions done by the optimization and control algorithm at an initial input velocity of 10 m/s which is reduced to 3m/s when the obstacle was ahead the road.

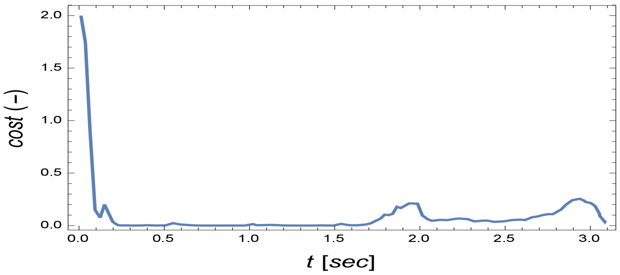

Fig. 5. The plot indicates the change of the cost function for the duration of the process.

During these results, when compared with the work in [7], it is noticed that the proposed approach in our work could control a vehicle at a considerably high velocity through a mathematical modeling that wasn't achievable in previous works. Through analyzing mathematical performance of the presented work, it was found that all mathematical constraints, which were faced during the control and optimization process, were successfully met. The proposed system could effectively avoid a collision based on the information given by data provided by means of V2V and V2I communication systems and also keep the vehicle in lane if there was no available information on an obstacle in addition to keeping vehicle's speed within road speed limits. More scenarios were tested but not included in the work due to limited space, therefore only interesting results were shown and discussed.

IV. CONCLUSION AND FUTURE PROSPECTS

During this work, an autonomous self-controlled vehicle framework for lane-keeping and obstacle-avoidance at low-velocity and high-velocity road conditions was presented. The presented article demonstrated the importance of utilizing V2V communication systems into the modeling framework by providing road data such as speed and obstacle's dimensions.

The future work will concentrate on improving the computation speed to reach the level of a ”in the loop simulation”. To reach the status of a in-loop computation a hardware implementation will be examined. An open problem is under which parametric values of the obstacle a stable solution for the vehicle can be found.

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