

## VEHICLE DYNAMICS PREDICTION MODULE

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**Abstract.** In this contribution we used the vehicle dynamics for creation a vehicle motion prediction module for autopilot tasks. A Vehicle Dynamics Prediction Module (VDPM) was created as an application for self-driving hardware assistance for high velocities maneuvering (above 40km/h). The dynamic characteristics of a vehicle have a complex mathematical mechanism, but have a regularity character. This fact allows us to create a basis with a limited number of pre-calculated maneuvers to describe the behavior of the vehicle dynamics for maneuvering in public roads.

**Keywords:** dynamics, modeling, prediction, trajectory, vehicle.

### 1. Background

Modern automotive industry is focused on self-driving vehicles and needs an appropriate virtual testing environment not only for sensor testing and visualization, but also for vehicle simulation dynamics. Planning autonomous or intelligent driving is divided into hierarchical classes. Generally, there are four classes: route planning, path planning, maneuver choice and trajectory planning [1]. Three of them (path, maneuver and trajectory) are components of autonomous on-road driving, which takes into account vehicular dynamics, obstacles, road geometry and traffic interactions. Often these three classes are combined as one. Route planning is concerned with finding the best global route from a given origin to a destination, supplemented occasionally with real-time traffic information.

The path is determined as a continuous sequence of initial and terminating configurations with the boundary conditions. Consequently, path-planning is the problem of finding a geometric path from an initial configuration to a given terminating configuration such that each configuration and state on the path is a feasible one. For driving autonomously on public roads the vehicle at each moment should be able to choose the best and safest maneuver to perform after finding the best geometric sequence of waypoints to follow. After finding the best path to follow and the best maneuver to perform, a trajectory must be generated such that the motion model and state constraints are satisfied and this trajectory guarantees comfort for a passenger and smoothness for a trip. The problem of generating a trajectory, according to the path and the maneuver, is foremost solved by selecting a geometric curve to ensure smooth motion through the road network. After that the trajectory is optimized by using a cost function according to the dynamic model and the presence of obstacles along that trajectory. There are many approaches to solve the problems of route, path and maneuver planning. They are described in Refs. [1-3] and are not considered in this work.

Majority of existing planning methods rely on bicycle or car-like kinematic model for modeling a vehicle, but these models cannot exploit the basic maneuver capabilities of the car, because it doesn't take into account, for example, tire forces. A few approaches [4, 5] have

utilized the dynamic approach based on the bicycle model, and consequently take into account the mass of the vehicle and friction. However, the dynamic model which efficiently describes the motion and the distribution of forces of the vehicle in a real-world environment is yet to be implemented. One of the big challenges is to capture and abstract a vehicle's capability and constraints and then introduce this information in maneuver and trajectory planning. Examples include acceleration, braking or steering constraints and the influence of weather or road surface on these capabilities or constraints.

Because the simulations of the vehicle physics (and dynamics) are complicated, it is unfeasible to use real-time and online simulations for vehicle trajectory prediction algorithms. This leads to alternative solutions like using the pre-calculated dynamic database. One of the biggest problems in vehicle dynamics is the tire kinematics behavior. The slip characteristics and the damping of the tires have a big influence on the vehicle steering capacities. The tire slip angle has a non-linear behavior that is a function of the steering angle and acceleration. These features must be considered during the steering path analysis and setting.

Nowadays, a lot of accidents occur as a result of misplaced perception and decision making on the part of the human driver. Autonomous driving is envisaged to considerably reduce these mistakes because accurate risk assessment is vital for preventing accidents. Despite current systems are successfully applied to finding paths and detecting obstacles in reality, accidents still happen. Therefore, big accent must be given to precise risk estimation in real-time.

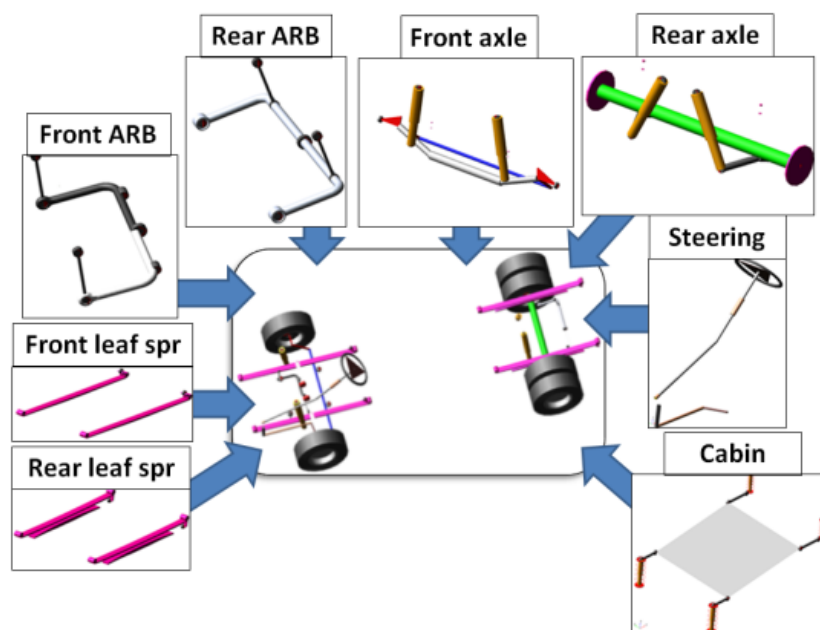
All sources [1-5] describe methods of route, path and maneuver planning that use strongly simplified car models. For correct real-time planning we need to consider the most realistic model of a car. The contribution of this work is to show the method of creation a vehicle motion prediction module for autopilot tasks with considering dynamic effects of all suspension parts using MBS model and also considering stiffness and damping of tires.

## 2. Modeling

There are three representative vehicles assigned to adjustment and test of the VDPM. All the vehicles will be modeled in MBS software with options like flex-body modeling. For this job MSC ADAMS-car has been chosen for the vehicle dynamic analysis. The virtual models of the representative vehicle have been created based on the study of every part.

At the first step, the vehicle needs to be separated into subsystems: body, front and rear axles, steering system, wheels, brakes and powertrain (Fig. 1). The body, power train, brakes and some subsystem parts usually are modeled as rigid parts (mass point), obviously only if they don't have any influence into the vehicle dynamics. It means, the compliance of the subsystems/parts should be analyzed and their global influence in the vehicle dynamic behavior has to be checked. The more relevant subsystems and parts are:

- *Body subsystem*: Bending and Roll stiffness are the most important characteristics of the vehicle (e.g. Body-on-frame trucks). If the stiffness of the vehicle is relatively low, the influence on the understeer characteristics of the suspension will be high. It means the body must be modeled as a flex body. One of the more relevant tests for the study of the understeer characteristics is the standard ISO 4138. This International Standard specifies the open-loop test methods for determining the steady-state circular driving behavior of passengers cars [6];



**Fig. 1.** Subsystems of the truck assembly.

- *Anti-roll bars (ARB)*: The stiffness of the ARB has the most significant on the suspension roll stiffness characteristics, and obviously the difference between the front and rear axle stiffness give us the understeer characteristic of the vehicle. This part can be modeled as flex-body or as two rigid bodies joined with a calculated torque able reproduce the flex-body roll stiffness characteristics;

- *Low stiffness parts*: In some vehicles (e.g. Lada Kalina) the lower control arms of the front suspension have a relatively low stiffness. This type of parts has to be modeled as flexible bodies, because they have some influence in the vehicle dynamics.

Usually, for the flex-body modeling in the MBS software the Craig-Bampton method is used. This method permit to get the linear deformation behavior of the body, based on the superposition of the normal modes [7]. This type of methods has low CPU requirements and are one of the more frequently used methods to speed up the CPU time. There are other methods, like co-simulation with finite-element solvers, but the CPU time cost is very high relatively to the flex-body ones. All these subsystems should be validated by natural tests rigs, like K&C. And then a final full vehicle dynamics validation must be performed, to be sure the MBS model of the vehicle is an accurate digital twin of the original one (e.g. ISO 7401 and ISO 4138).

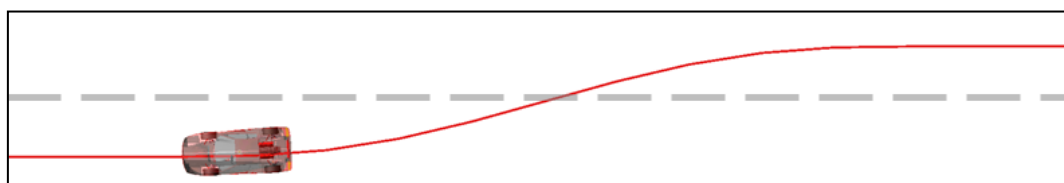
The next step is to simplify the models without losing precision. This is done by replacing flexible bodies with equivalent simple elements, e.g. anti-roll bars can be modeled as two rigid bodies and equivalent forces, the lead springs of the trucks and etc.

### 3. Virtual maneuvers

The target of the VDPM use is the prediction and rating of maneuver dynamic parameters of the vehicle. To create a database of maneuvers, it is crucial to parameterize them. Then the parameterized maneuvers are classified as standard maneuvers. If a maneuver cannot be parameterized, it is classified as non-standard. For instance, usually single lane change is designed by smooth paths. The input parameters of the maneuver are: road friction, vehicle speed, longitudinal and lateral target displacement. In the maneuver parameterization step this maneuver will be classified as standard. For this job, the assigned standard maneuvers are:

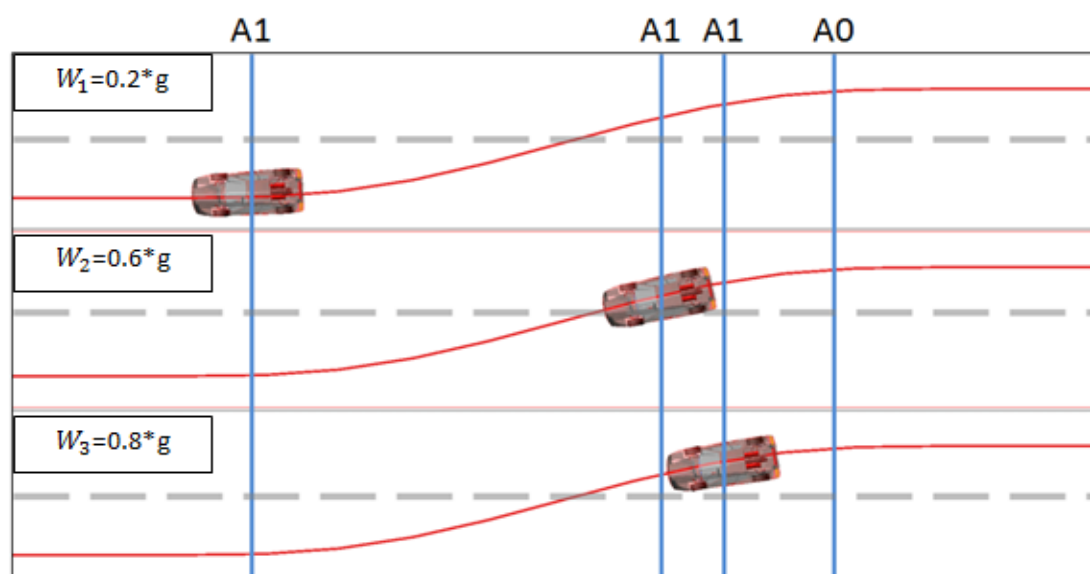
- *Lane change*: In Figure 2 the lane change trajectory of a vehicle is designed as a smooth curve. A quintic polynomial is used to describe this curve from the start point to the final point

of the maneuver. The lateral displacement is based on the lane road width standards and vehicle dimensions. The longitudinal displacement is limited by the vision sensors range.



**Fig. 2.** Lane change maneuver.

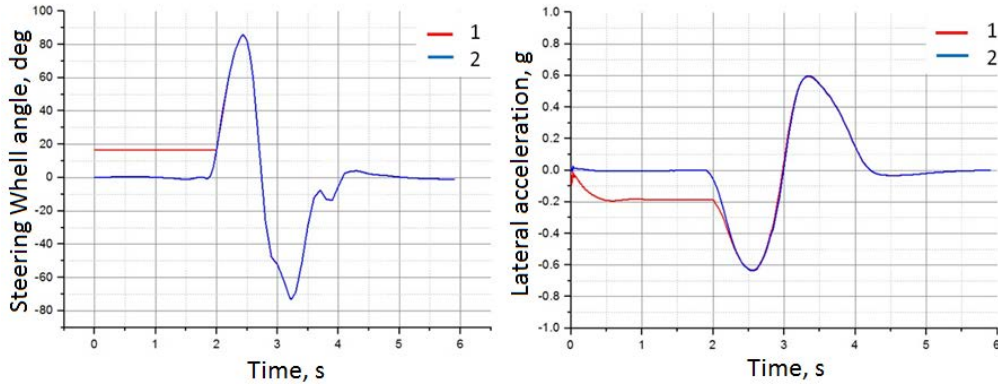
- *Evasive maneuver*: this maneuver is simulated for a given initial trajectory based on the lane changer maneuver and initial speed. At the same time, at the beginning of the lane change maneuver from point A0 to A1 (Fig. 3), the car was subjected to a longitudinal acceleration, corresponding to braking (direction is opposite to the vehicle direction). The final target is to define the stop time, the path derivation and the slip angle of the vehicle. An example of the study of the evasive maneuver for a light vehicle with a start speed of 40km/h and different acceleration values is shown in figure 3.



**Fig. 3.** Evasive maneuvers (40km/h).

The problem of the non-standard maneuvers will be solved by an interpolation and stitch of primitive maneuvers.

- *Primitive maneuvers*: to understand and to use the primitive maneuvers it is necessary to understand the vehicle response to a direction change. In Figure 4 the peculiar graphics of the steering path and lateral acceleration for lane change maneuvers are shown. Here curve 1 is a lane change start with a non-zero initial steering angle, and curve 2 is for a zero initial steering angle. As can be seen, the two steering paths are similar at the time 2s, but the acceleration is similar only at the time ~2.3s. The acceleration graphic shows that the vehicle response to the steering change is ~0.3s. It means that the path of the vehicle will be identically at the time ~2.3s. The approbation of this effect allows one to stitch different parametrical (standard) maneuvers for reproducing a non-standard maneuver.

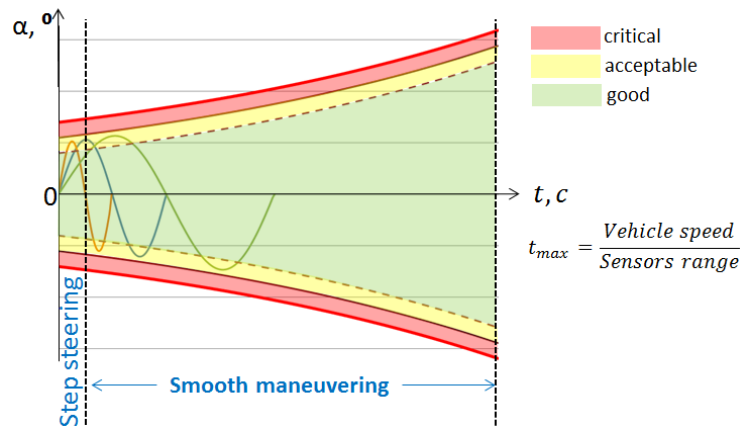


**Fig. 4.** 1-steering path, 2-lateral acceleration.

The last affirmation helps us to understand the primitive maneuvers stitching logic. But the study of the equivalence of the vehicle dynamics during the last maneuvers is not only based on the lateral acceleration; it is also necessary to take a look to the slip angle of the tires, roll angle of the vehicle, etc.

#### 4. Pre-run simulations

Before the VDPM starts the database generation, the information of the primitive maneuvers functions and the vehicle physical limits must be given. The primitive maneuvers functions are designed using standard functions for the selected self-driving inputs and steering actuator capacities. Therefore, these functions depend on the particular automobile and also on the self-driving algorithms they are generated for. To obtain the vehicle physical limits, it is necessary to study the vehicle capacity to reproduce the required steering inputs inside a safe maneuvering area. To define the physical limits of the vehicle several tests are run [8]. This step gives us the possibility to reach the critical values and dependencies of the automobile dynamic parameters, e.g. the maximum lateral acceleration, as functions of the steering values and steering speeds. The analysis of this information helps us to create rating criteria for the vehicle maneuvers. The steering capacities of a vehicle are represented in Figure 5. In this figure three rating areas can be found. These areas are separated by step steering and smooth maneuvering by the steering path timing. The values of these areas change from vehicle to vehicle. It is also important to note that the higher the steering speed signal, the lower the vehicle is able to reproduce the steering amplitude. The information about maneuvers and their real values are not presented in this paper because this information is confidential.

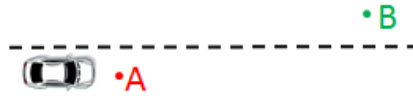


**Fig. 5.** Steering path working area.

### 5. Fitting algorithm

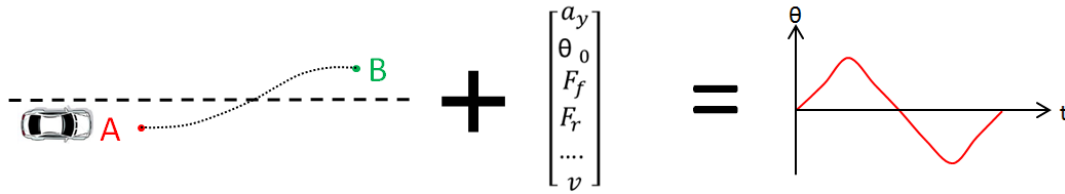
The procedure of the VDPM is described by the following basic steps:

1. The autopilot has a task to move from point A to point B, e.g. single lane change shown in Figure 6.



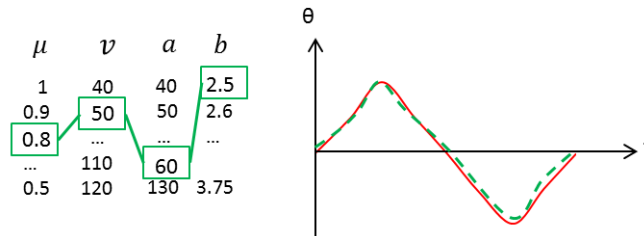
**Fig. 6.** Single lane change.

2. In this step, the autopilot creates a reference road course from point A to point B. A steering input is calculated by the autopilot algorithms. The steering input is based on the initial conditions of the vehicle at point A (e.g. velocity, steering angle, etc.) and is illustrated in Figure 7.



**Fig. 7.** Maneuver inputs.

3. Then using the initial conditions of the vehicle and the steering input, the VDPM is able to find a solution from the pre-calculated simple maneuvers database. After the solution with the initial conditions is found, the VDPM compares the autopilot and the database steering input.



**Fig. 8.** Maneuver searching.

4. Then the difference (error) between the autopilot and VDPM steering inputs is calculated (Fig. 8):

If the error is lower than a defined threshold, the VDMP database outputs the predicted output parameters array. The output parameters describe the vehicle dynamic status on the way from point A to point B. The evaluated output parameters, for example, are: path derivation, wheel forces balance, lateral acceleration, roll angle, vehicle slip angle, etc.

If the error is higher than a defined threshold and the steering inputs differs, the VDPM searches a solution with a parameters array based on primitive maneuvers. These maneuvers have a limited number of variations. And all these variations cover every possible dynamic behavior of the vehicle. Interpolation algorithm is responsible of finding the required function and computes the corresponding parameters array.

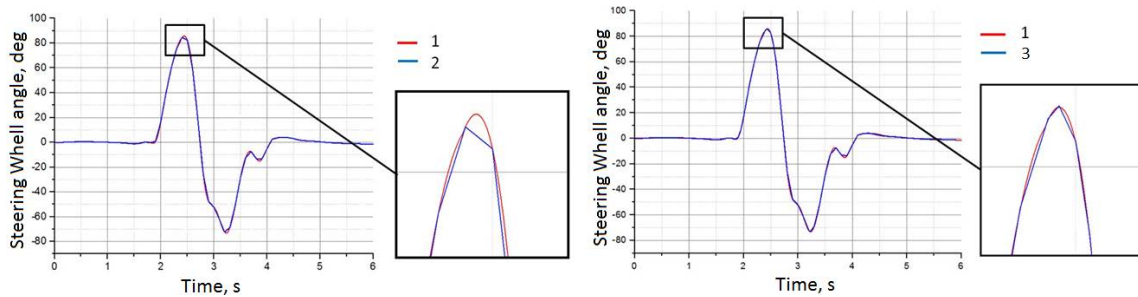
Once a solution is found, the VDPM creates an output parameters array of the vehicle from point A to point B as an interpolation, and stitches primitive maneuvers. The created

output parameters array describes the vehicle dynamic behavior on the course from point A to point B by discrete steps  $i$ . The procedure of the last algorithm can be described as a maneuver division into  $n$  steps, based on the vehicle steering response characteristics. The output parameters at step  $i$  solution are used as input parameters for searching and interpolate a solution in the database for the next step  $i+1$ . At the final step, after all the solutions are found, they are stitched in.

## 6. Database optimization and CPU time and searching

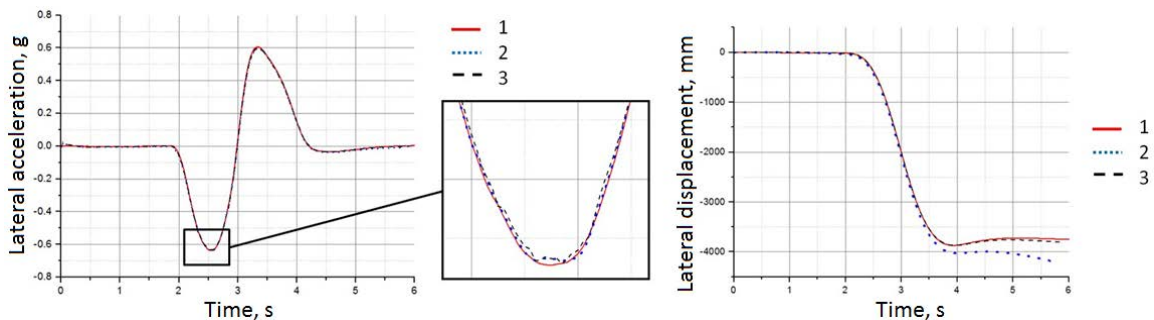
To optimize the database generation and its usage, a few techniques were adopted from the time step for calculations to the memory use during the database search process:

1. Time step: early, in Figure 4 the peculiar steering path was mentioned. Now, we will try to study the influence of the discretization of this path by two ways. In Figure 9, we have a discretization of the steering path (curve 1) with a fixed time step of 0.1s in the left side (curve 2), and in the right side, the same discretization method but with the count of the function extremums (curve 3).



**Fig. 9.** Steering path discretization.

The results of the discretization methods show the influence of the extremums count in the steering path function (fig. 10). As we can see, the lateral acceleration is very similar to in all 3 cases, but the lateral displacement show a big derivation from the original one when the steering path extremums are not on count.



**Fig. 10.** Results of the steering path discretization methods.

The last affirmation force us to use the discretization process to run the MBS analysis, but only if the extremums of the steering function is on count.

The next step is the optimization of the memory usage. There exist vehicle state parameters that will not change abruptly while the vehicle is moving, e.g. the velocity or friction coefficient. Therefore, to speed-up the VDPM response, a several number of decisions are fixed;

The database has a subordination order, from the parameters with the lower changes during the vehicle movement to the parameters with the higher changes, e.g. the friction coefficient with the road is the first search parameter, then the speed, etc;

The VDPM is always working while the vehicle moves, and a corresponding searching corridor is loaded to the memory all the time. The limits of this corridor are the minimum and maximum probable “parameters” moving corridor of the automobile in the current movement case. This corridor permits to constrain the searching process and load only the needed segment of the database.

## 7. Summary and conclusions

The three MBS models of the vehicles were created to test and calibrate the VPDM. All these models were optimized to reach more rapid testing without any loss of accuracy on the dynamic behavior of the vehicles.

The VDPM considers the physical limits of the vehicle. Because these limits are known, the VDPM describes all the maneuvers inside safe maneuvering areas. The non-pre-simulated maneuvers (non-standard) are described by stitching primitive maneuvers.

## Acknowledgement

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