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Effects of Tire and Anti-Roll Bar Stiffness on Vehicle Handling

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Abstract

Handling is one of the important criteria in evaluating vehicle dynamics. Improving the handling first requires defining sub-targets and their acceptable ranges, and then finding the under-control parameters with the most effects on sub-targets. These are the focus of this research that is performed for an N2 pickup truck. After simulating the under-study (default) vehicle and its benchmark (target) vehicle, standard handling tests according to ISO are performed to compare the results of the two vehicles. Constant radius cornering and step steer tests are identified as appropriate representatives of the handling. Roll angle, understeer coefficient, lateral deviation, and yaw rate are defined as sub-targets. Tires and anti-roll bar stiffnesses are selected to examine their effects on sub-targets. Sensitivity analysis based on a design of experiment method and analysis of variance is a tool to examine the effectiveness of parameters on the outputs. The complicated nonlinear vehicle model is substituted with some quadratic regression models to be used for optimization by the response surface method. The obtained optimum solution is verified using the nonlinear model and it is illustrated that changing the selected parameters can make the handling like the benchmark vehicle.

Keywords: Vehicle Handling; Tire; Sensitivity Analysis; Optimization.

1. Introduction

In the vehicle development system, target cascading has great importance. Targets are generally at the product level, and the goal is to propagate product-level specifications to appropriate specifications at the subsystems level. The four steps of product design are specifying the product's general targets, defining sub-targets (target cascading), designing or modifying the subsystems and their components to satisfy sub-targets, and verifying the product at the system level based on the defined targets [1]. In the automobile industry, vehicle design targets are related to safety, vehicle dynamics, NVH, fuel economy, emission, etc. The focus of this research is on vehicle dynamics with the aim of improving the handling behavior of an under-study vehicle with the primary specification set (called default vehicle) to have behavior like the benchmark vehicle. So, the benchmark vehicle is the target vehicle to compare the results with it.

Improving handling and stability has been studied in different aspects. Some researchers tried to design a new suspension system, such as [2], some used an active controller to enhance the behavior, like [3], while others preferred optimizing the under-control parameters for this aim. The third category of articles investigated changing the suspension geometric parameters [4], tire parameters [5, 6], suspension hard point coordinates [7], stiffness and damping coefficients of the suspensions [8], bushing installation and stiffness [9], etc. The mentioned papers evaluated the results based on arbitrary tests, like constant radius cornering, J-turn, frequency response, sine with dwell, swept-sine input, and double lane change. None of the mentioned articles examined all dynamic tests suggested by the standard to more accurately choose the best test for evaluating vehicle behavior. Furthermore, the interactive effects of parameters on targets have not been shown.

This paper introduces a procedure for defining sub-targets, improving handling behavior by optimizing the parameters, and verifying the results at the product level by checking the target. After simulating the full-vehicle model, five standard tests are performed and two tests covering the vehicle behavior in the other tests are selected. Four sub-targets are defined for the two selected tests. This is the procedure of propagating targets to the sub-targets. The full-vehicle model is so complicated to be used for optimization. So, it is replaced by a simple model. Seven under-control parameters are selected to be optimized to improve the handling. Considering the selected factors and four sub-targets, a design of the experiment method (DOE), a small-central composite design (small-CCD), is implemented. Analysis of variance (ANOVA) illustrates the effectiveness of the selected parameters on the outputs and provides simple regression models as substitutes for the full-vehicle model describing the relationships between factors and sub-targets. Interaction effects between selected factors are shown and then, the optimum set of factors is selected using the response surface method (RSM) to make the under-study vehicle behavior like the benchmark. The case study is an N2 pickup truck, but the procedure is implementable for all types of vehicles.

The rest of the article is organized as follows: The next section introduces the dynamic simulation model and standard handling tests and then compares the results of the vehicle with the benchmark to select the sub-targets. Section 3 concentrates on the sensitivity analysis of sub-targets to the under-control design parameters. The regression models proposed in Section 3 are used in Section 4 for the optimization of design factors to improve the handling. The optimum solution is also verified in Section 4. Finally, the summary and conclusions are given.

2. Dynamic Simulation & Problem Statement

This section first states how the vehicle has been modeled for this research and gives the specifications of the under-study vehicle. Then, introduces the standard tests to evaluate the handling behavior of the vehicle. After briefly presenting the simulation results, sub-targets are selected to be studied in the next section to improve the vehicle handling behavior.

2.1 Modelling

The vehicle is modeled in ADAMS/CAR software by creating different subsystems including front suspension, rear suspension, steering, driveline, powertrain, transmission, chassis frame, body, tires, and brake system. This paper focuses on improving the handling behavior of a pickup truck in the N2 category. Fig. 1 shows the schematic view of the RWD pickup in ADAMS/CAR software. The front suspension is a double-wishbone suspension with a torsion bar, tension rod, and anti-roll bar. The vehicle has leaf springs in the rear suspension.

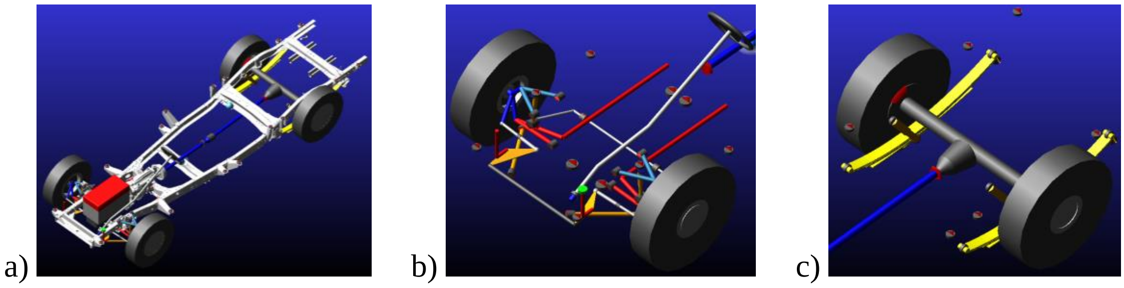


Figure 1. Vehicle in ADAMS/CAR: a) Full-vehicle b) Front suspension and steering c) Rear suspension.

Some vehicle parameters are listed in Table 1. The center of gravity of the vehicle has been measured according to ISO 10392 in the prototyping department of Zamyad Co. The reference coordinate frame is in the middle of the front axle and the x-axis is toward the rear. Each part's mass has been measured and then, the CG (center of gravity) and mass moment of inertia have been calculated using the CAD model. Tire stiffnesses in three directions have been measured in the laboratory under different loads and internal air pressure, by Kavir tire. Spring and shock absorber data have been received from the manufacturers.

Table 1. Vehicle parameters

Parameter	Unit	Value
GVW (Gross Vehicle Weight)	kg	3800
CG location (x-axis, z-axis)	mm	2387, 617
Wheelbase	mm	3385
Equivalent spring stiffness (front, rear)	N/m	35376, 151074
Shock absorber damping coefficient (front, rear)	N.s/m	4235, 3059
Anti-roll bar torsional stiffness	N.m/rad	1545
Tire width (front, rear)	mm	189, 216
Tire radius (front, rear)	mm	388, 400
Front tire stiffness (radial, translational, lateral) under GVW	N/mm	461, 363, 246
Rear tire stiffness (radial, translational, lateral) under GVW	N/mm	640, 276, 290

2.2 Vehicle Handling Evaluation

Given the application of the vehicle, handling behavior is more important that the ride quality, although checking the ride performant is necessary following reaching the handling objectives. This subsection briefly introduces the standard handling tests, targets, and simulation results for the under-study and benchmark vehicle, and finally defines sub-targets.

2.2.1 Standard Tests

ISO standard proposes some tests to quantify the handling characteristics of a vehicle in the N2 category. Some of them that are selected to be checked in this report are:

- **Steady-state cornering** (ISO 14792)- constant radius: To check the understeer behavior, the vehicle is driven on a path with a standard radius of 100 m, starting from a minimum speed. The speed is gradually increased to reach the maximum possible while maintaining the radius.
- **Single lane change** (ISO 14791)- sine wave steering input: One full period sinusoidal-wheel input with the predetermined steering-wheel amplitude shall be applied. The tracking ability and reaction time of the vehicle to the steering input for obstacle avoidance are evaluated.
- **On-center handling** (ISO 11012)- weave test: This is an open-loop test to check the steering system and tie characteristics. The steering wheel is subjected to an oscillatory input, usually sinusoidal.
- **Step steer input** (ISO 14793): The object of this test is to determine the transient behavior of a vehicle subjected to step steer inputs with increasing amplitudes.

- **Braking in a turn** (ISO 14794): This test determines the effect of braking on course holding and directional behavior of a vehicle, whose steady-state circular motion is disturbed by braking action.

2.2.2 Targets

The vehicle handling behavior is compared with the benchmark vehicle that has the same GVW, but a smaller cargo box (161 mm higher CG height) and 355 mm shorter wheelbase. The benchmark has been manufactured and its desired behavior has been confirmed. So, the objective at the product level is to reach the benchmark handling characteristic by analyzing the handling tests' outputs like yaw rate, lateral acceleration, sideslip angle, roll angle, and understeer coefficient. Sub-targets are defined by comparing the results and selecting the most effective criteria.

2.2.3 Results and Sub-Targets

A comparison of the pickup behavior with the benchmark is summarized in Table 2. The understeer coefficient of the pickup is small. The vehicle roll angle is less than the benchmark due to the lower CG height resulting from the bigger cargo box, assuming uniform loading. Single lane change, on-center handling, and step steer tests contend that the vehicle is slow in responding to the steering input. The behavior of the vehicle in braking in a turn test is acceptable.

Table 2. Handling behavior comparison of the under-study vehicle and the benchmark vehicle

Test/ Analysis	Criteria	Unit	Under-study vehicle	Bench vehicle
Steady-state cornering	Understeer coefficient	-	2.5	0.8
	Sideslip angle gradient	deg.s^2/m	4.3	4.2
	Lateral acceleration peak	m/s^2	0.1	0.1
	Roll angle gradient	deg.s^2/m	0.66	0.46
	Roll angle peak	deg	0.71	0.50
	Yaw rate gradient	deg.s/m	4.4	4.4
Single lane change	Roll angle peak	deg	0.43	0.24
	Sideslip angle peak	deg	1.9	1.4
	Yaw rate peak	deg/s	6.2	5.2
	Lateral acceleration peak	G	0.06	0.05
On-center handling	Lateral acceleration at steering wheel angle of 50 deg	g	0.05	0.03
	Yaw rate at steering wheel angle of 50 deg	deg/s	11	9
Step steer	Yaw rate peak	deg/s	9.6	6.9
	Lateral acceleration peak	g	0.15	0.10
Braking in a turn	Yaw rate peak	deg/s	5.8	5.7
	Lateral acceleration peak	g	0.10	0.10
	Sideslip angle peak	deg	3.2	2.9

So, the behavior of the under-study pickup is required to be improved in terms of the understeer coefficient, and steering effort (or reaction time). The sub-targets listed in Table 3 must be studied more in-depth. The objective is to increase the understeer coefficient, lateral deviation, and yaw rate along with keeping the roll angle less than the value for the benchmark.

Table 3. Defined sub-targets to enhance handling

Analysis	Sub-target	Unit	Bench Value	Current Value	Objective
Steady-state cornering	Maximum roll angle (MRA)	deg	0.71	0.5	<= target
	Understeer coefficient (USC)	-	2.5	0.8	Increase
Step steer	Maximum lateral deviation (MLD)	m	36.3	30.0	Increase
	Maximum yaw rate (MYR)	deg/s	9.6	6.9	Increase

3. Sensitivity Analysis

Sensitivity analysis is used to examine the effectiveness of under-control parameters on sub-targets (mentioned in Table 3). Under-control parameters in this study are tire and anti-roll bar parameters that have been suggested by automobile experts to be modified to enhance handling behavior. A DOE method is used to set the factor levels intelligently and get the best results from the ANOVA. This section describes the application of DOE in this study, presents the ANOVA results, discusses the results, and provides the main and interactive effect of parameters on sub-targets. By confirming the effectiveness of suggested parameters by the experts, the optimization problem can be implemented to find the optimum solution to achieve the sub-targets, and eventually targets.

3.1 Design of Experiment

Small-CCD has shown its capability in finding sensitive parameters and understanding non-linear relationships with a few runs [10]. So, this method is used here. Seven design variables are front and rear tire stiffnesses in radial, tangential, and lateral directions and anti-roll bar torsional stiffness. The factors' levels are given in Table 4. Small-CCD in Design-Expert software proposes 45 combinations of levels to compute the outputs for them. To find the outputs (sub-targets listed in Table 3), two tests (steady-state cornering and step steer) must be performed for each set of factors.

Table 4. Axial levels (AL), factorial levels (FL), and the center point (CP) of factors

Factor	Unit	Low AL	Low FL	CP	High AL	High FL
Front and rear tire radial stiffness (VS_F, VS_R)	N/mm	50	200	450	700	850
Front and rear tire tangential stiffness (TS_F, TS_R)	N/mm	190	250	350	450	510
Front and rear tire lateral stiffness (LS_F, LS_R)	N/mm	90	150	250	350	410
Anti-roll bar torsional stiffness (ARB)	N.m/rad	800	2000	4000	6000	7200

3.2 Regression Models

ANOVA suggests quadratic models describing relationships between outputs and design factors, with the p-value and adjusted R-squared given in Table 5. The low p-value and high adjusted R-squared show the effectiveness of selected factors on sub-targets. Therefore, the parameters can be optimized to change the output and achieve the objectives mentioned in Table 3 using the regression models. It must be noted that finding the optimum points by the ADAMS/Car model is so time-consuming, and using these simple models speeds up the optimization procedure.

Table 5. Fit statistics of the quadratic regression models proposed by ANOVA

Output	p-value	Adjusted R-squared
Maximum roll angle	0.0003	0.9064
Understeer coefficient	<0.0001	0.9340
Maximum lateral deviation	0.0008	0.8367
Maximum yaw rate	0.0003	0.9676

3.3 Sensitive Parameters

Figure 2 compares the "1 – p-value" of design factors in terms of different sub-targets. A higher value means a lower p-value and more effectiveness on the output.

According to the figure, tire lateral stiffness has an incredible effect on vehicle handling behavior. All selected parameters have considerable influence on vehicle roll angle. Reaction time (in the form of maximum lateral deviation and yaw rate) is affected by the anti-roll bar coefficient and rear tire tangential stiffness, in addition to the lateral stiffness of tires. So, the suggested parameters by the experts are influential and the handling behavior can be improved by them.

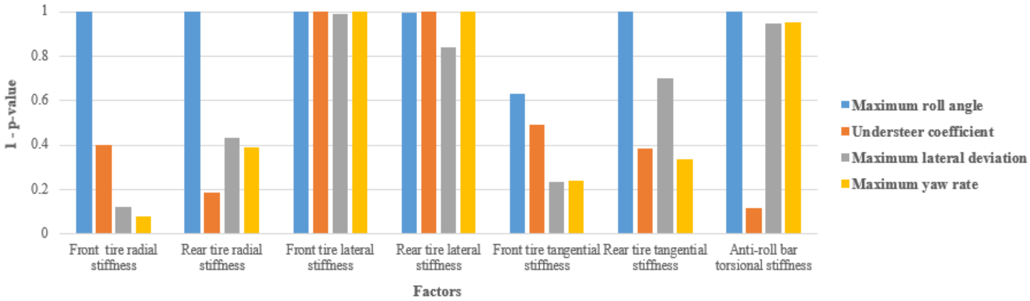


Figure 2. Effectiveness of different factors on sub-targets.

3.4 Interactive Effects

Interactive effects illustrate how simultaneously changing two parameters affects the responses, provided that the other factors are fixed at their center points. These effects are depicted in Fig. 3 by contour plots for the most effective parameters on each output. By changing parameters together, more enhancement in sub-targets can be achieved. The roll angle decreases by increasing the vertical stiffness of all tires (Fig. 3.a). Increment in front tires' lateral stiffness and decrement in rear tires' lateral stiffness result in more reduction of roll angle (Fig. 3.b and Fig. 3.c), but it may lead to oversteer behavior (Fig. 3.g), increment in lateral deviation with slow reaction time (Fig. 3.h), and high yaw rate with controllability reduction (Fig. 3.k). Consequently, a compromise between sub-target is needed. As another example, increasing the rear tires' tangential stiffness results in a lower roll angle (Fig. 3.e), but makes the response slow (Fig. 3.i).

It can be concluded that interactive plots give a good insight into the problem. By employing an optimization algorithm and defining the target values, an optimum point can be found to improve vehicle handling to an acceptable level compared to the benchmark.

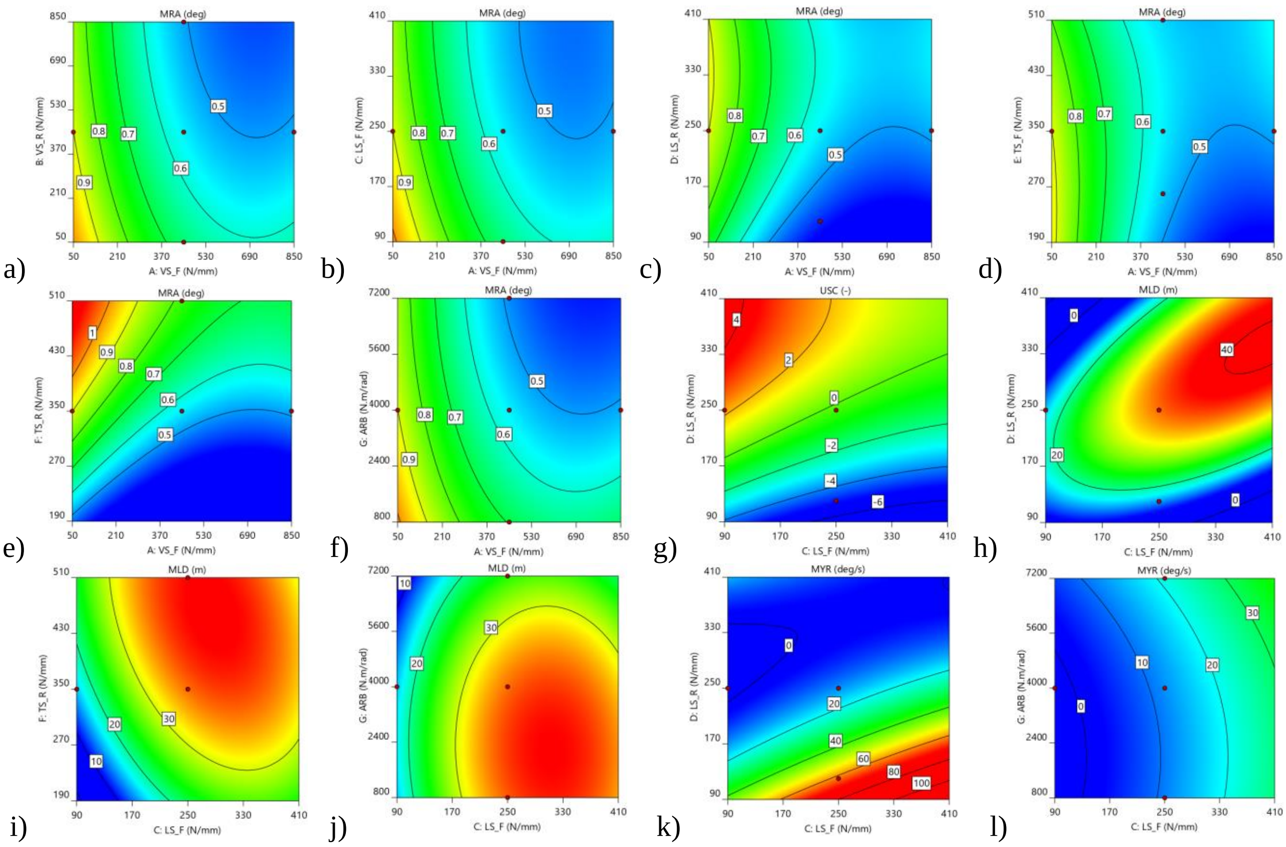


Figure 3. Simultaneous effects of factors on sub-targets (Abbreviations were defined in Table 3 and Table 4).

4. Vehicle Handling Improvement

Regarding the difference between the handling behavior of the under-study pickup and benchmark, reported in Table 3, this section attempts to improve the handling using the regression models obtained from ANOVA in the previous section. Since the regression models are approximations of the nonlinear model in ADAMS software, although they are simple to be used in the optimization problem, the optimum point resulting from them is required to be verified. The optimization procedure and the obtained results are concerns of this section.

4.1 Optimization

Design variables studied in sensitivity analysis are optimized with objectives reported in Table 3. The RSM is used in Design-Expert software. Optimum parameters are given in Table 6.

Table 6. Optimum vehicle parameters, leading to better handling

Parameter	Unit	Optimum Value
Front tire stiffness (radial, translational, lateral)	N/mm	268, 300, 279
Rear tire stiffness (radial, translational, lateral)	N/mm	513, 319, 277
Anti-roll bar torsional stiffness	N.m/rad	5391

The optimum parameters result in the sub-targets mentioned in Table 7 using the approximate regression models. The maximum roll angle of the optimized solution is a bit more than the default one, but it is still less than the benchmark vehicle and acceptable. The understeer coefficient has been changed from 32% of the coefficient for the benchmark to 76% of it. The maximum lateral deviation and the maximum yaw rate specifying the steering effort and reaction time to the input have been increased to the approximately same values as the benchmark vehicle.

Table 7. Effects of optimum vehicle parameters on sub-targets

Sub-target	Unit	Target Value	Before Optimization	After Optimization
Maximum roll angle	deg	<=0.71	0.5	0.53
Understeer coefficient	-	2.5	0.8	1.9
Maximum lateral deviation	m	36.3	30.0	36.2
Maximum yaw rate	deg/s	9.6	6.9	9.8

4.2 Verification

To verify the optimum point resulting from the regression models of ANOVA, the optimum parameters are imported to the nonlinear ADMS model and handling tests introduced in section 2.2.1 are performed. Some results of each test are depicted in Fig. 4 to Fig. 8. It can be seen in all tests that the response time of the vehicle has been improved to the benchmark vehicle, looking at the x-y and yaw rate plots. The roll angle of the vehicle is less than the benchmark vehicle and it is desired. The handling behavior of the optimized vehicle is acceptable and final verification must be done after manufacturing tires and anti-roll bars with optimal specifications reported in Table 6.

5. Summary/ Conclusion

This research has focused on improving the handling behavior by the procedure that is also useful in other cases. The under-study vehicle has been an RWD N2 pickup truck that is desired to be modified in a way to have the handling behavior like the benchmark. The vehicle has been simulated and five standard tests including constant radius cornering, single lane change, on-center handling, step steer, and braking in a turn have been performed. By examining the results, the handling target at the product level has been stated in terms of four sub-targets, comprising roll angle, understeer coefficient, lateral deviation, and yaw rate. The sensitivity of the defined sub-targets to the under-control parameters comprising tires’ stiffnesses in three directions and anti-roll bar torsional stiffness has been analyzed by Small-CCD and ANOVA. The sensitive parameters on each output have been recognized and their interactive effects on objectives have been discussed. Finally, the design parameters have been optimized using RSM and the regression model resulted from ANOVA, as a substitute for the complicated simulated full-vehicle model. The optimized results have been verified using the main model. It has been shown that implementing the procedure has resulted in handling behavior like the benchmark vehicle and is even better in terms of roll angle.

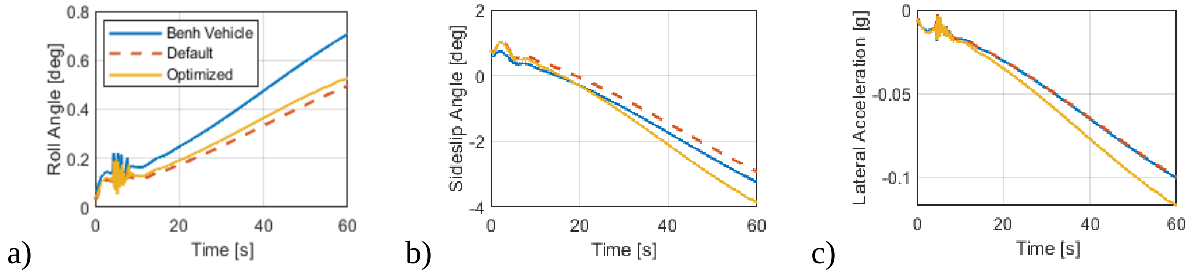


Figure 4. Results of constant radius cornering test.

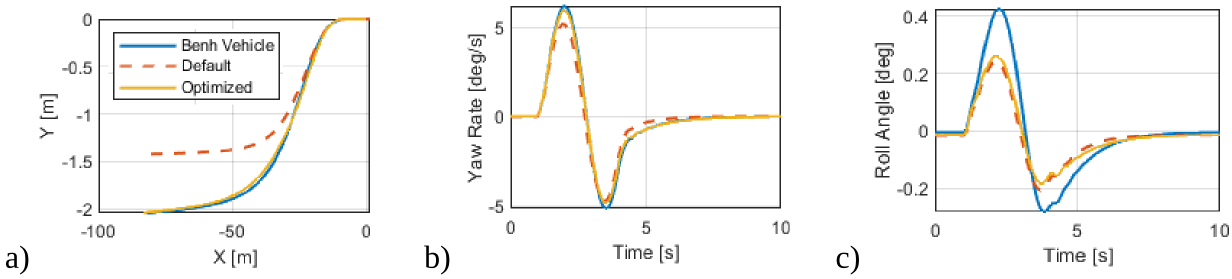


Figure 5. Results of single lane change test.

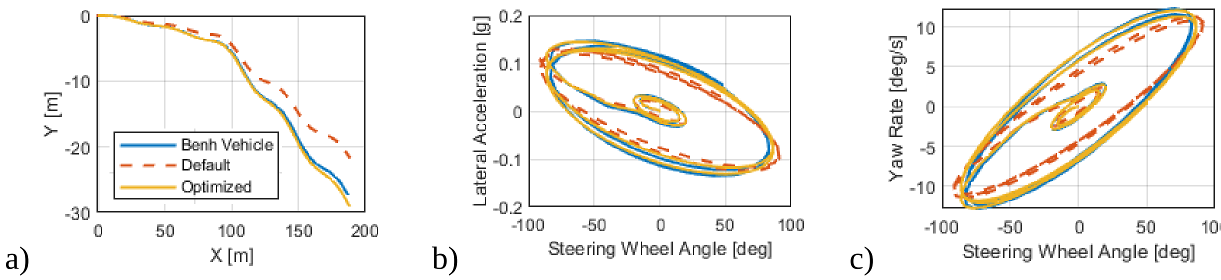


Figure 6. Results of on-center handling test.

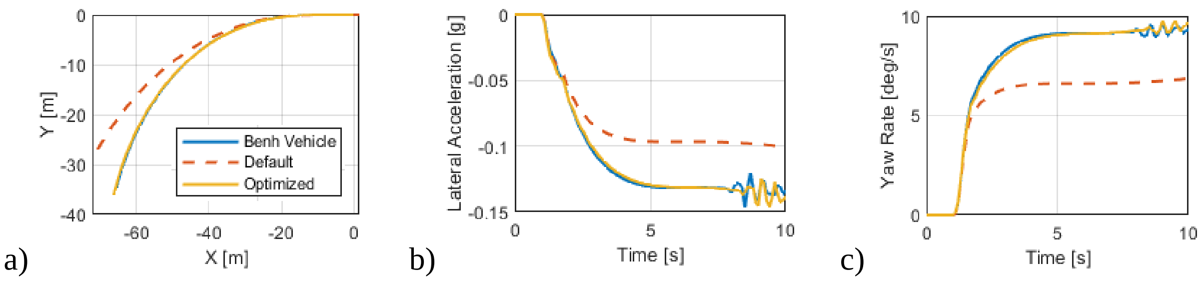
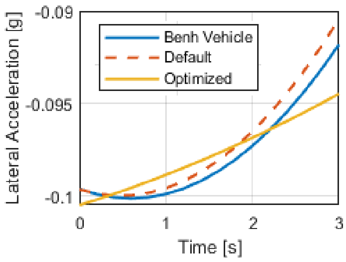
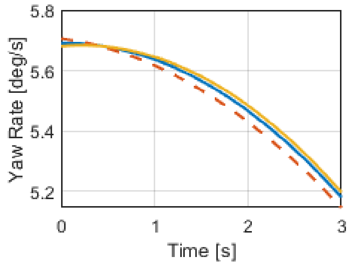


Figure 7. Results of step steer test.





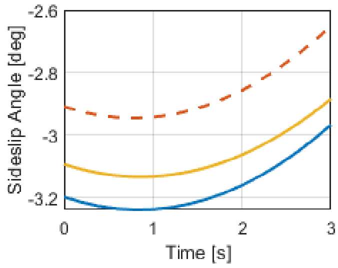


Figure 8. Results of braking in a turn test.

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