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To cite this article: Doyeong Kim *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **491** 012005

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Improvement of Modeling Consistency for Vehicle Dynamic Analysis Using Design of Experiment

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Abstract. In the present study, a development method for high-accuracy dynamics models using Design of Experiments (DOE) was proposed based on experimental results obtained in full-vehicle dynamic testing. In vehicle dynamics modeling, the design parameters of each model need to be experimentally obtained by measuring their characteristic values or referring to detailed information regarding those models so that these design parameters can be reflected in the modeling process; however, in practice, it is difficult to gain access to detailed information for most design parameters. To analyze the effects on vehicles of design parameters for which relevant data have not been acquired, DOE tools available in Minitab, a statistical analysis program, were employed. As a result, it was possible to identify major design parameters that affected the behavior of vehicle models, and a method to improve the consistency of vehicle models by preferentially modifying those major design parameters was proposed.

1. Introduction

In attempts to improve automotive fuel efficiency, global car manufacturers are continuing to develop high-efficiency powertrain systems, including AMT and DCT; at the same time, the scope of applications is now extending to not only passenger vehicles but also commercial vehicles. Most 3.5-ton small- and medium-sized commercial vehicles on the road in Korea are fitted with manual transmissions and are currently making a gradual shift to automatic transmissions.

Developing a new powertrain system requires pretesting that occurs when the system is equipped into vehicles. Considering safety issues and costs, however, vehicle dynamics simulations are widely carried out on developed products as pre-tests to improve their integrity. Again, high-accuracy system and vehicle modeling are required as prerequisites for those vehicle dynamics simulations.

In general, vehicle dynamics simulations are performed based on characteristics test results of essential auto parts, such as dampers, springs, and bushing. Commercial vehicles, however, are equipped with parts that are more robustly designed compared to those used in passenger vehicles, and their relevant characteristics data, including Center of Gravity (COG) positions and tire property data, are not as general as those of passenger vehicles. As a result, high-accuracy modeling of commercial vehicles is more challenging overall.

In the present study, a method of using Design of Experiments (DOE) to efficiently implement vehicle modeling was proposed based on test results of full-vehicle dynamic testing. In Section 2, details on full-vehicle testing to assess vehicle dynamics and existing modeling methods are described. In Section 3, a method of using DOE to improve the consistency of vehicle modeling is proposed.



Finally, details about vehicle models with improved consistency as a result of the proposed method are described, and major findings of the present study are specified in the Conclusion.

2. Vehicle Modeling for Vehicle Dynamics Analysis

2.1 Full-vehicle Testing to Developing Vehicle Models

Full-vehicle dynamic testing of a target vehicle was conducted to develop corresponding vehicle models. Here, a 3.5-ton commercial vehicle manufactured by the H motor company was selected as the target vehicle, and special experimental environments for full-vehicle tests were created. In the meantime, the vehicle was fitted with various instrumentation devices, including a telemetry system to measure the torque of the propeller shaft, a Global Positioning System/Inertial Navigation System (GPS/INS) to estimate the dynamic behavior of the vehicle, and a data acquisition system to store measurement data. Experimental environments were configured as shown in Fig. 1.



Figure 1. Test Vehicle Setting

A total of ten full-vehicle dynamic tests were performed, including five lateral dynamics tests and five longitudinal dynamics tests. Considering the special operating conditions of commercial vehicles, the same test was conducted twice in succession: once without live load and the other under live load[1]. By doing so, the effect of live load on the dynamic characteristics of the vehicle was determined and analyzed. Testing scenarios are shown in Table 1 below.

Table 1. Vehicle Dynamics Test Scenarios

Test Classification	Test Scenario	reference
<i>Longitudinal Dynamics Test</i>	Acceleration Test – APS 50%, 100%	KATECH
	Deceleration Test – DCC 0.3g, 0.5g	KATECH
	Coast-down Characteristic Test	KATECH
	Hill Climbing Characteristic Test	KATECH
	Downhill Characteristic Test	KATECH
<i>Lateral Dynamics Test</i>	Double Lane Change Test	ISO-3888
	Slalom Test	KATECH
	Steady-State Cornering Test	ISO-4138
	Continuous Sinusoidal steering test	KATECH
	J-turn test	ISO-7401

2.2 Vehicle Modeling

The development process of vehicle modeling in the present study is shown in Fig. 2. Trucksim, a commercial modeling tool made by Mechanical Simulation, was employed for commercial-vehicle modeling, and data acquired from characteristics testing of essential auto parts were used in the modeling. Subsequently, the consistency improvement process for the developed lateral-direction vehicle model was carried out during 107 iterations of trial and error by varying each of the design parameters based on experience and know-how accumulated during previous vehicle modeling studies. Determination coefficients used for verification of modeling consistency are shown in Eq. (1).

$$\rho(A, B) = \frac{1}{N-1} \sum_{i=1}^N \left(\frac{A_i - \mu A}{\sigma A} \right) \left(\frac{B_i - \mu B}{\sigma B} \right) \quad (1)$$

μA and σA are the average and standard deviation, respectively, of A values.

μB and σB are the average and standard deviation, respectively, of B values.

The lateral-direction consistency improvement process was conducted based on the results of double-lane change testing; as a result, a vehicle model was developed to provide lateral-correlation properties, as follows: Lateral-Acceleration at 96.40% and Yaw-Rate at 99.70%. The result set of vehicle consistency were configured as shown in Fig. 3.[2]

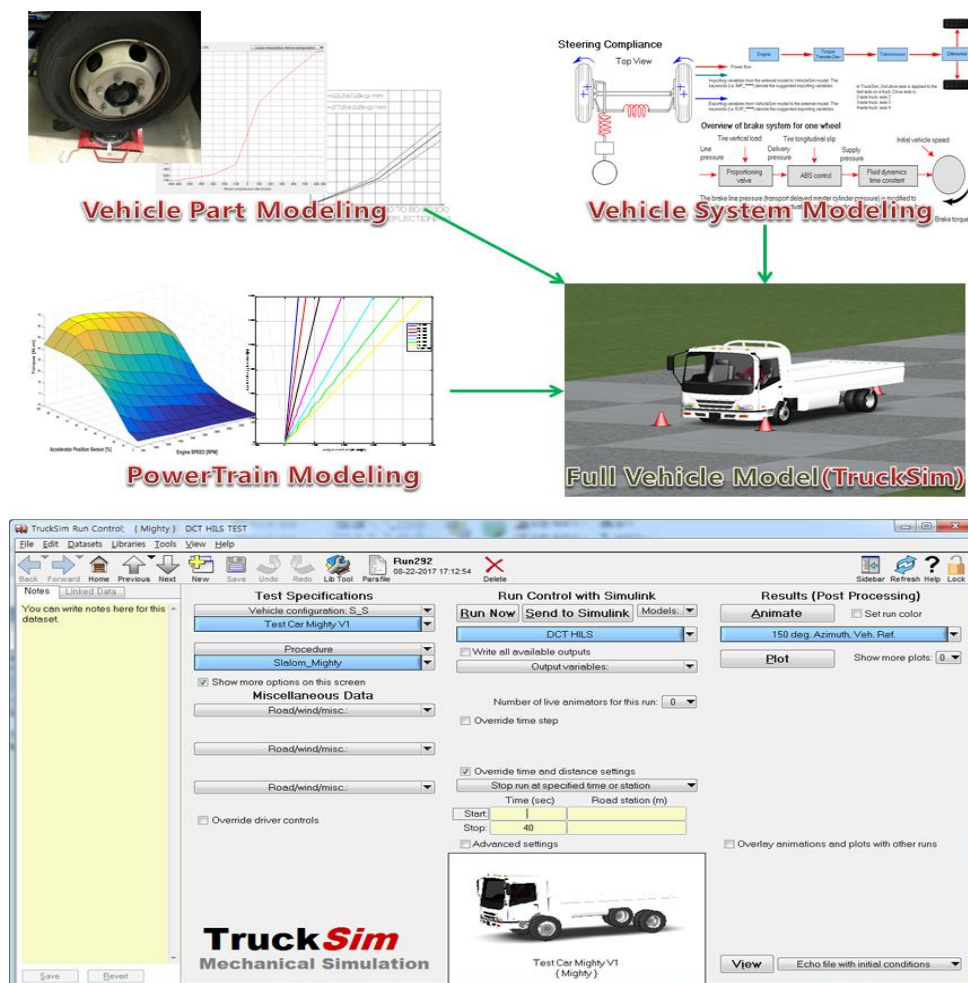


Figure 2. KATECH Vehicle Dynamics Model Develop Process

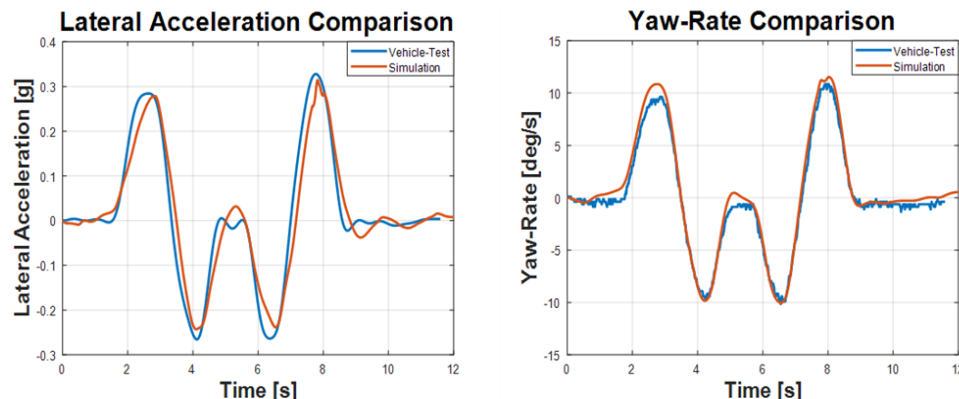


Figure 3. Vehicle Test and Simulation Result comparison of Lateral Acceleration & Yaw-Rate

3. Improvement of Vehicle Model Consistency Using DOE

3.1 Parameter Selection for Simulation

Among various factors other than spring constant and damper characteristics curves, which were acquired from the essential auto part testing, eight factors were selected as design parameters for the simulation, including the COG height, COG position with respect to front tires (weight ratio between the front and rear wheels), front tire stiffness, rear tire stiffness, stabilizer constant, camber, toe value, and caster.[3] To analyze the effects of adjusted combinations of the eight parameters on the lateral-direction behavior of the vehicle, DOE tools available in Minitab, a statistical analysis program, were employed[4]. A design parameter table for DOE was developed, as shown below, to ensure that each arrangement set the resolution to a value of 4, so that only the combination of primary effects of the design parameters without interaction components could be reflected and analysed[5]. Also, another 16 simulations were run based on a dataset that was generated by adding weighted values of +1 and -1 to the basic dataset of the vehicle model developed in 2.2.

Table 2. Design Parameter Combination for DOE.

Run Order	C.O.G. Height	FR : RR Weight Ratio	Front Tire Stiffness	Rear Tire Stiffness	Stabilizer Constant	camber	Toe	Caster
1	800	1700	1.1	0.9	600	1	-1	1
2	800	1300	0.9	1.1	800	1	-1	1
3	840	1700	0.9	0.9	800	1	-1	-1
4	800	1300	0.9	0.9	600	-1	-1	-1
5	840	1700	1.1	1.1	800	1	1	1
6	800	1300	1.1	0.9	800	1	1	-1
7	800	1700	1.1	1.1	800	-1	-1	-1
8	840	1300	1.1	0.9	800	-1	-1	1
9	840	1300	0.9	1.1	800	-1	1	-1
10	800	1300	1.1	1.1	600	-1	1	1
11	840	1300	1.1	1.1	600	1	-1	-1
12	840	1700	0.9	1.1	600	-1	-1	1
13	800	1700	0.9	0.9	800	-1	1	1
14	840	1300	0.9	0.9	600	1	1	1
15	800	1700	0.9	1.1	600	1	1	-1
16	840	1700	1.1	0.9	600	-1	1	-1

3.2 Analysis of Primary Effects Based on Simulation Results

Based on the results of the 16 simulation runs, as shown in Table 2, the effect of each design parameter on the behavior of the vehicle was analyzed. Here, the DOE tools of Minitab were used, while the response was set to be the lateral correlation of the vehicle's Lateral-Acceleration. As a result, the strongest determining factor for the vehicle's Lateral-Acceleration was found to be the COG position with respect to the front tires (weight ratio between the front and rear wheels), followed by the COG height and the stabilizer constant. The Yaw-Rate was determined to be most significantly affected by the COG position with respect to the front tires (weight ratio between the front and rear wheels), followed by the toe values. The standardized effect for Lateral-Acceleration and Yaw-rate were configured as shown in Fig. 4 and 5.

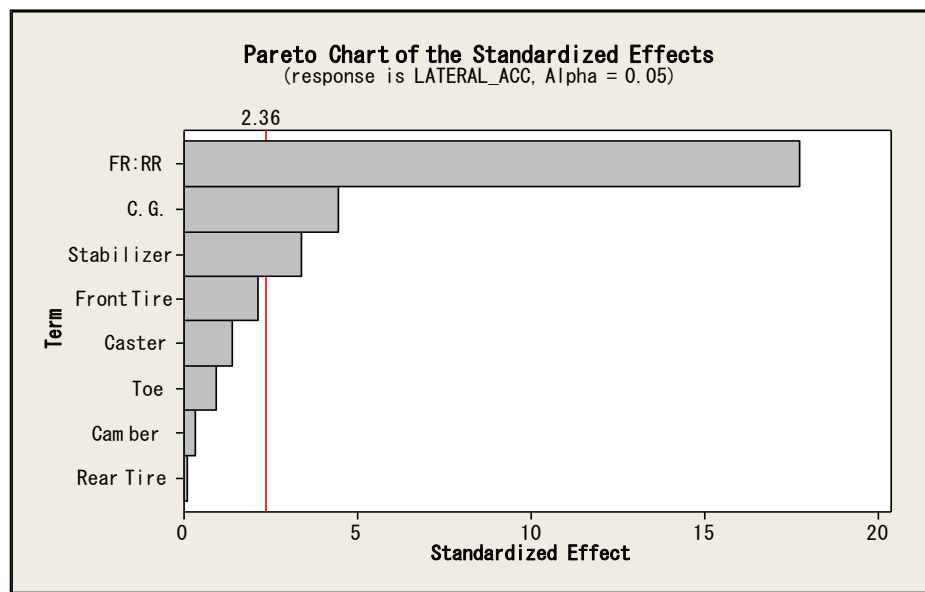


Figure 4. Pareto Chart of the Standardized Effect : Lateral Acceleration

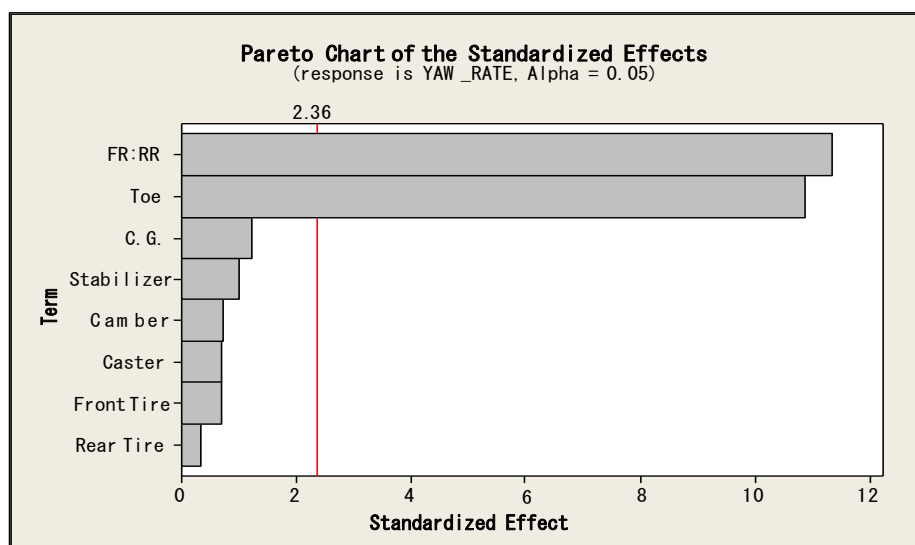


Figure 5. Pareto Chart of the Standardized Effect : Yaw-Rate

3.3 Improvement of Simulation Consistency by Changing Primary Effects

As can be seen in the 16 simulation-run results shown in Table 2, Run Order 6 had the highest consistency in both Lateral-Acceleration and Yaw-rate. All Run Orders recorded over 99% consistency in the Yaw-Rate, and thus additional simulations were conducted by setting as a design parameter the weight ratio between the front and rear wheels, the primary determining factor of Lateral-Acceleration. The results are shown in Table 3.

Table 3. Results of Additional Simulations

FR:RR Weight Ratio	1100	1200	1300	1400	1500
Lateral-Acceleration	97.54	97.38	97.17	96.98	96.74
Yaw-Rate	99.75	99.77	99.76	99.75	99.73

Additional simulation results showed that the smaller the weight ratio became, the higher the consistency was in the Lateral-Acceleration. The consistency in the Yaw-Rate, however, was the highest when the COG position with respect to the front tires was set to 1200. Therefore, the optimized design parameter for the vehicle was determined to be a COG position with respect to the front tires of 1200.

4. Conclusions

In the present study, eight determining parameters to improve the consistency of vehicle models were selected, including COG height, COG position with respect to front tires (weight ratio between front and rear wheels), front tire stiffness, rear tire stiffness, stabilizer constant, camber, toe value, and caster. Using these parameters, a Design of Experiments (DOE) method was employed to determine the optimized modeling consistency conditions, as follows:

1) In the present study, most determining factors for the consistency of vehicle modeling, which are difficult to experimentally characterize, were confirmed. By doing so, the effects of these parameters on the lateral-direction characteristics of the test vehicle were demonstrated and analyzed; as a result, the strongest determining factor was confirmed.

2) A consistency improvement process was performed by adjusting the design parameter that had been determined to most significantly affect the modeling consistency, leading to improvement as follows: consistency in the Lateral-Acceleration improved from 96.40 to 97.38% and consistency in the Yaw-Rate improved from 99.70 to 99.77%. Improvement data results were configured as shown in Fig. 6.

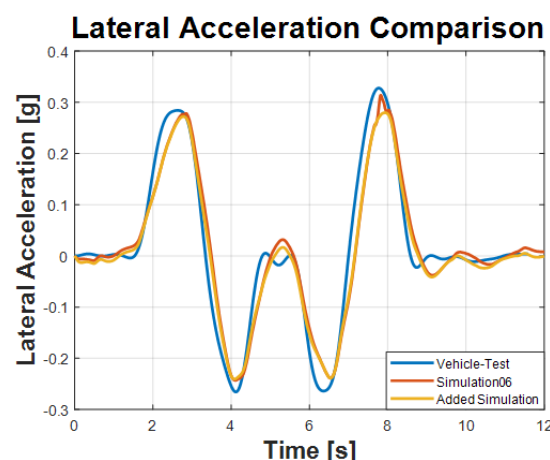


Figure 6. Result of Vehicle Modeling Consistency Improvement : Lateral-Acceleration

3) Through these procedures, a vehicle model with improved modeling consistency was developed. Also, it was confirmed that the application of this DOE based method significantly reduced the time needed to implement consistency-improving procedures in vehicle models.

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