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Assessing Lateral Stability of Long Combination Vehicles Using Stochastic Modeling of Varying Operating Conditions and Parameter Uncertainties

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***Abstract*— Long combination vehicles (LCVs) have been increasingly applied for highway freight transportation due to their improved fuel economy and reduced greenhouse emissions. However, LCVs exhibit poor high-speed lateral stability owing to their multi-unit structures, large sizes, and high center of gravity (CG). Given the unique dynamic features of these large vehicles and varied operating conditions, LCVs' lateral stability is difficult to predict. To date, simulation has been widely used to evaluate the dynamic performance of road vehicles. High fidelity simulations may provide excellent insights into the dynamics features of LCVs under a predefined operating condition. However, under varying operating conditions and in the presence of vehicle parameter uncertainties, it is difficult to use simulation for reasonably evaluating the lateral stability of LCVs. To address this problem, we propose an effective simulation method, which consider different road conditions and trailer payload variations using Monte Carlo based stochastic modeling method. The numerical simulations are executed on a co-simulation platform, consisting of TruckSim for LCV modelling, MatLab/SimuLink for updating vehicle model and operating condition, and Python for data management and analysis. Simulation results demonstrate the effectiveness of the proposed stochastic modeling method.

Keywords: stochastic modeling; long combination vehicles; high-speed lateral stability assessment; varying operating conditions; vehicle parameters uncertainties; co-simulation

I. INTRODUCTION

To date, simulation has been increasingly applied to the design and development of road vehicles [1]. The past two decades witnessed extensive applications of numerical simulations for assessing the directional performance of articulated heavy vehicles (AHVs) [2]. LCVs can decrease fuel-consumption and green-house-gas emission by approximately one-third [3]. Thus, in recent years, LCVs been increasingly applied for highway freight transportation. However, due to LCVs' multi-unit structures, large sizes, and CGs, these exhibit poor high-speed lateral stability. To ensure the safety of LCVs, simulations have been conducted to evaluate the lateral stability in rearward amplification (RWA), which is defined as the ratio of the maximum lateral acceleration of the rearmost trailer to that of the tractor over a high-speed evasive maneuver [4]. Most of simulations are specified under a given operating condition and predefined vehicle system parameters [5]. In this situation, it is difficult to comprehensively evaluate the direction performance of AHVs under varying operating conditions and in the presence of vehicle system parameter uncertainties [6].

However, under varying operating conditions and in the presence of vehicle parameter uncertainties, it is difficult to use simulation for effectively evaluating the high-speed lateral stability of AHVs and, in particular, LCVs [7]. To address this issue, this paper proposes a stochastic modeling method considering varying operating conditions and in the presence of vehicle parameter uncertainties. In the Monte Carlo based stochastic modeling method, with the specified operating conditions and vehicle model parameter uncertainties in terms of variation range, mean, and standard deviation, the Python software generates the required data for co-simulations. The LCV model is developed in TruciSim package. MatLab/SimuLink updates the operating condition and vehicle parameters values considering the predefined vehicle parameter uncertainties and varied operating conditions. With the intended virtual tests specified by the Python software, the co-simulations are conducted by integrating the LCV model and updated operating condition. The co-simulation results will be analyzed by the Python software to attain the associated stability performance measures. Co-simulations are conducted to study a B-double dynamics under a single lane-change maneuver with forward speed ranging from 85 to 95 km/h, road surface friction coefficient ranging from 0.35 to 0.9, trailer payload ranging from 13,000 to 19,000 kg, and the height of trailer CG ranging from 2,250 to 2,350 mm. The co-simulations provide required performance measures reflecting the impacts of the above variation factors. It is demonstrated that the proposed stochastic modelling technique successfully achieves the full matrix of performance measures by conducting much smaller number of simulation runs.

The rest of the paper is organized as follows. Section II introduces the proposed stochastic modeling method. The selected simulation results are analyzed and discussed in Section III. Finally, the conclusions are drawn in Section IV.

II. Proposed Stochastic Modeling Method

A. *Stochastic Modeling Method*

The stochastic modeling method based on Mont Carlo technique is developed to conduct for assessing the effects of random road condition, trailer loading, and vehicle speed on the high-speed of AHVs. The co-simulation platform is built using Python, MATLAB/Simulink, and TruckSim. This method is intended to reduce the computational efforts of a full matrix of simulation runs of various loads and road conditions.

As shown in Figure 1, varying operation conditions are defined by the range, mean, and standard deviation of corresponding parameters including trailer loading condition and road surface friction coefficient. The Python program is developed to generate a full look-up table of the varying operation condition considering the mean, range, and standard deviation with the assumption of the normal-distribution. The Python program also functions to conduct postprocessing including calculation and plotting figures. A total number of simulation runs needs to be defined, for example, and the simulation will begin with randomly selecting a set of parameter values in the generated normal-distributed tables. Based on the randomly selected variable values, a corresponding AHV model will be generated in TruckSim software with updated trailer loading and road condition, e.g., tire/road interaction. Then the updated AHV parameter values and road information will be imported to MATLB/Simulink testing environment as a format of VS function. The MATLAB/Simulink testing environment contains the target trajectory. After one simulation run, the acquired data, such as lateral acceleration and yaw rates, will be saved to a local file. If the simulation run is not the last one, then the results of this run will be stored to a local file for later usage and analysis. The Python code will select another set of parameter values randomly from the look-up tables, and the procedure of updating vehicle model and road condition repeats till the termination run number is reached. Finally, the Python code collects the acquired data from each run, evaluates performance measures, e.g., path-following errors and RWA, as well as draws plots of results.

B. *Modeling of LCVs*

In this research, TurckSim software is used to generate a 3-D model of an LCV with the configuration of B-train double. The selection of the high-fidelity TruckSim model for the evaluation stems from the expectation to authentically simulate the high-speed lateral stability of the LCV. It is shown that the vehicle roll and tire dynamics of the LCV imposes an important effect on the high-speed lateral stability of the vehicle [8]. Therefore, simplified linear yaw-plane model might not be applied to simulate the high-speed lateral stability accurately.

Figure 2 shows the B-train double model generated using TruckSim, which utilizes a symbolic multibody program, VehicleSim (VS) Lisp, to generate equations of motion for the 3-D multibody vehicle system [9, 10]. As seen in Figure 2, the configuration of the B-trail double is specified as "S_SS+SSS+SSS", where "S" denotes a solid axle, an underscore "_" a separation of axle groups, a "+" a fifth-wheel or pintle-hitch connecting two vehicle units. The VS Lisp takes each of the LCV configurations in geometric terms, that is, body degrees-of-freedom, point mass locations, directions of force vectors, etc. With the respective configuration information, the VS Lisp derive the vehicle models in ordinary differential equations (ODEs), and generates computer source code (e.g., C) to solve the ODEs.

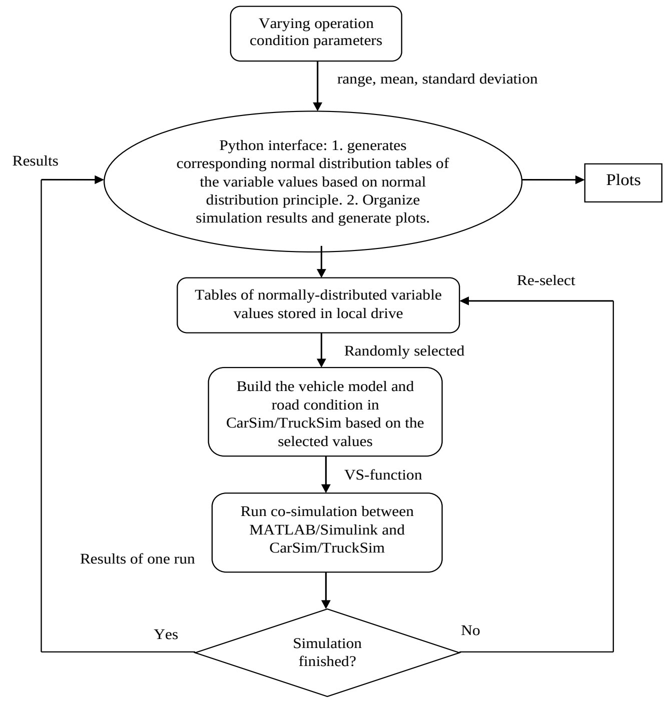

Figure 1: Flowchart of the stochastic modeling method.

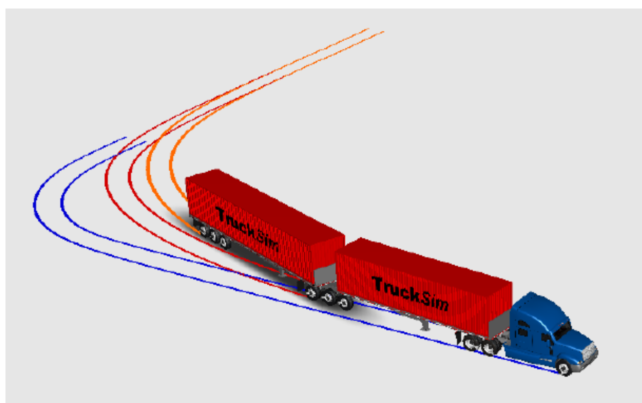

Figure 2: The 3-D TrcukSim model of a B-trail double.

TruckSim software mainly comprises the VS browser, the TruckSim database, and the VS solver. The VS browser serves as a graphical user interface to TruckSim. With the TruckSim database, the B-train double configuration can be selected, for which vehicle system parameters, tire/road interactions, test maneuvers, etc., are defined, and the ODEs are generated. The VS solver solves the ODEs and executes dynamic simulations. The VS browser can be applied for numerous applications, e.g., co-simulations specified in MatLab/SimuLink accessing to the TruckSim database via an interface, i.e., S-function.

C. *Simulation Environment*

The simulation environment in the stochastic modeling method involves 4 specific aspects, namely, tire/road interaction in friction coefficient, trailer payload, vehicle forward-speed, and trailer CGs. Simulations have been conducted using the B-train double generated in TruckSim. To evaluate the lateral dynamics of the LCV, the high-speed single lane-change (SLC) testing maneuver recommended by ISO-14791 is simulated [11, 12]. Figure 3 shows the predefined testing course of the SLC maneuver, over which the LCV is controlled to track the testing course with the lateral displacement of 3.5 m at a constant vehicle forward speed. For the stochastic modeling and simulation, the associated values for vehicle parameters and operating conditions are summarized in Table 1. As listed in the table, the vehicle forward-speed, tire/road friction coefficient, trailer payload, and trailer CG height vary from 85 to 95 km/h, 0.35 to 0.9, 13,000 to 19,000 kg, and 2,250 to 2,350 mm, respectively. In addition, the respective values of mean and standard deviation are also provided in the table.

According to the data provided in Table 1, 5,000 data sets are randomly generated, and the corresponding look-up table is fabricated. Note that each data set can be used to run one simulation. It is assumed that over a testing maneuver, for the B-train double, two trailers are assumed to have the same CG, and the same trailer payload, and the tire/road friction coefficient and vehicle forward-speed remain constant. For the closed-loop SLC testing maneuver, the built-in driver model in TruckSim is incorporated [9].

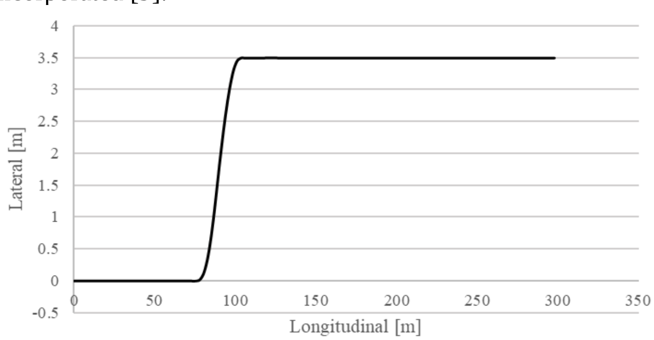

Figure 3: The testing course for the high-speed SLC maneuver.

TABLE I. THE VALUES OF VEIHCLE PARAMETERS AND OPERATING CONDITIONS FOR THE STOCHASTIC MODELING AND SIMULATION

Parameters	Minimum	Maximum	Mean	Standard Deviation
Speed/km/h	85	95	90	1
Tire/road friction coefficient	0.35	0.9	0.5	0.2
Trailer payload/kg	13,000	18,000	155,00	1,000
Trailer CG height /mm	2250	2350	2300	10

Given the randomly selected 5,000 data sets, the normal-distribution of the vehicle and operating parameter values are presented in the histograms as shown in Figure 4 (a) to (d).

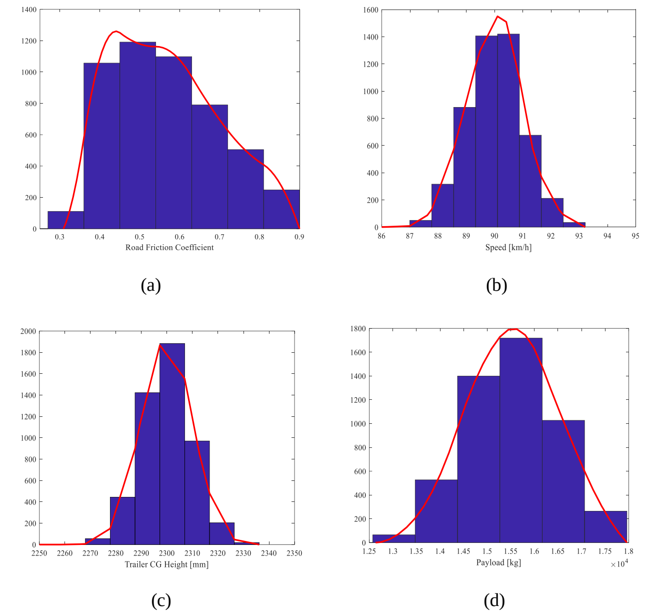

Figure 4: The normal-distribution of: (a) tire/road friction coefficient, (b) vehicle forward-speed, (c) trailer CG height, and (d) trailer payload.

III. SIMULATION RESULTS AND DISCUSSION

The stochastic modeling and simulation results of the B-train double are presented and discussed in this section. The selected lateral dynamic responses of the LCV are shown in lateral accelerations and trajectories of the tractor and the second trailer, as well as the RWA. The high-speed lateral stability measure of RWA is an indicator of the unique dynamic phenomenon of AHVs, in which the rearmost trailer exaggerates the lateral motion of the tractor under evasive maneuvers at high speeds. The RWA is one of the well-accepted measurements to represent the lateral stability of AHVs. To ensure good directional performance in path-following off-tracking and high-speed lateral stability, the desired RWA value is 1.0 [13].

As show in Table I, the SLC testing maneuver is implemented at a constant speed randomly selected from the range from 85 to 95km/h. Figures 5 to 7 show the effect of tire/road friction coefficient on the B-train lateral stability in terms of the maximum tractor lateral acceleration, the maximum rearmost trailer lateral acceleration, and the RWA, respectively. Within the low tire/road friction coefficient range, i.e., less than 0.5, as seen in Figure 6, the second trailer may experience a high lateral acceleration up to 0.85 g, and the data points (represented by circles) are loosely and randomly scattered within the lateral acceleration range from 0.47 to 0.85 g. However, within the same tire/road friction coefficient range, as shown in Figure 5, the data points of the tractor lateral acceleration are scattered relatively closely and densely, indicating that the maximum tractor lateral acceleration increases with the tire/road friction coefficient. Thus, it can be deduced that within the low tire/road friction coefficient range, the tractor remains its lateral stability, while the second trailer may experience larger lateral accelerations that can be provided by the tire/road adhesion capacity, thereby losing its lateral stability. Interestingly, in the low tire/road friction coefficient range, as shown in Figures 6 and 7, the pattern of the data point scattering of the RWA measure looks like that of the lateral acceleration of the second trailer. This phenomenon may be interpreted by the fact that in the low friction coefficient range, the tractor's lateral acceleration and the tire/road friction coefficient exhibits an approximate deterministic relationship, thus, the data points scattering pattern of the RWA is mainly dependent upon that of the lateral acceleration of the second trailer. As illustrated in Figure 7, in the low friction coefficient range, the RWA measure can be as large as 2.5.

However, when the tire/road friction coefficient is higher than 0.6, as illustrated in Figures 7 and 8, the data points of the lateral acceleration of the second trailer motion and the RWA are scattered more closely and densely. Interestingly, the lateral acceleration of the tractor is still increasing gradually with the friction coefficient. Thus, in the high friction coefficient range, both the leading and trailing vehicle units experience stable lateral motion in the SLC maneuvers.

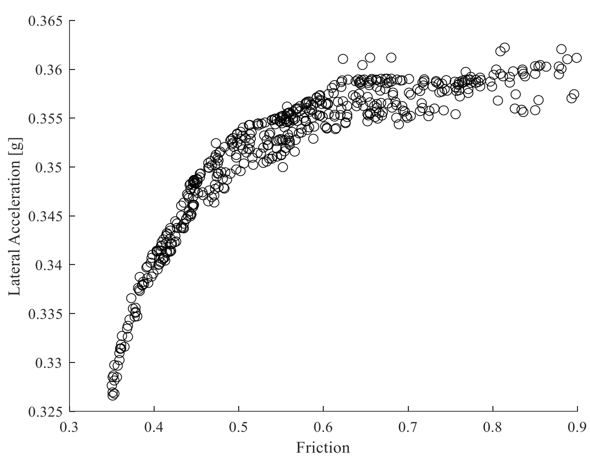

Figure 5: Tire/road friction coefficient vs. maximum tractor lateral acceleration.

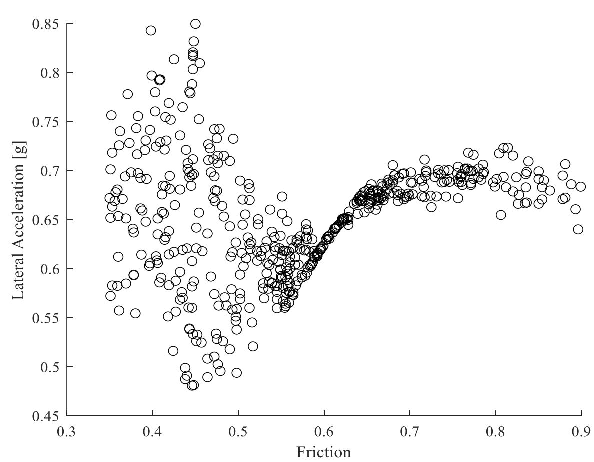

Figure 6: Tire/road friction coefficient vs. the maximum rearmost trailer lateral acceleration.

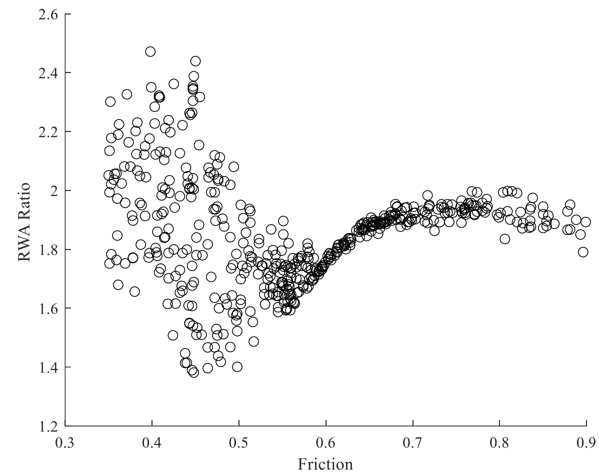

Figure 7: Tire/road friction coefficient vs. the RWA of B-train double.

To further investigate the effect of tire/road friction coefficient of the lateral stability of the LCV, the path-following performance of the vehicle is examined under different friction coefficients. In the simulation runs 5, 28, and 44, the tire/road friction coefficients are 0.471, 0.36, and 0.774, respectively. Figures 8 to 11 show the lateral dynamics of the LCV of the simulation runs of 5, 28, and 44 in terms of the tractor's trajectories, the second trailer's trajectories, the tractor's lateral accelerations, and the second trailer's lateral accelerations, accordingly. It is observed by inspecting Figure 8 that regardless of the vehicle forward speed, trailer payload, and trailer CG height, the overshoot of the tractor's lateral displacement over the SLC maneuvers increases with the decrease of tire/road friction coefficient. The peak value of the path-following off-tracking of the tractor reaches 0.3 m. It is also found that in the case of path-following off-tracking of the second trailer, the lower the tire/road friction coefficient, the larger the overshoot of the second trailer's lateral displacement of the evasive maneuvers. However, in the later case, the path-following off-tracking values of the second trailer are 1.1, 2.0, and 3.5 m while the tire/road friction coefficient takes the values of 0.774, 0.471, and 0.36, respectively. Note that the measure of path-following off-tracking is defined as the maximum lateral displacement derivation of the vehicle unit with respect to the predefined testing course. Apparently, the rearward amplification level enlarges with the decrease of the tire/road friction coefficient.

Figure 10 shows the lateral accelerations of the tractor with the tire/road friction coefficients taking the value of 0.36, 0.471, and 0.774. Surprisingly, it is observed that the maximum peak lateral accelerations of the tractor with different tire/road friction coefficient are almost the same (approximately 0.35 g) even though the friction coefficient varies from 0.36 via 0.471 to 0.774. A close observation of Figure 10 discloses that the lower the friction coefficient, the longer the settle time the tractor takes. Figure 11 reveals an interesting phenomenon that in the the sinewave lateral acceleration of the second trailer, the maximum peak values are 0.72, 0.48, and 0.41 g under the tire/road friction coefficient of 0.774, 0.471, and 0.36, respectively. The observed phenomenon discloses an important fact that over the high-speed SLC maneuvers, in the sinewave lateral acceleration of the second trailer, the maximum peak lateral acceleration of the vehicle unit is determined by the tire/road friction coefficient. Thus, the higher the friction coefficient, the larger the maximum peak lateral acceleration of the rearmost trailer. However, after the time period equivalent to the first sinewave, in the case of the tire/road friction coefficient of 0.774, the amplitude of latera acceleration of the second trailer becomes smaller, and eventually the oscillation of the lateral acceleration is damped out. On the other hand, in the case of the tire/road friction coefficient of 0.35, after the time duration equivalent to the first sinewave, the amplitude of lateral acceleration of the second trailer increases as time goes, and eventually the vehicle unit loses its lateral stability.

This research also explores the effects of forward speed, trailer payload, and trailer CG height on the lateral accelerations of the tractor and the second trailer, as well as the RWA and path-following off-tracking of the B-train double. The achieved results are consistent with those published in [14-20].

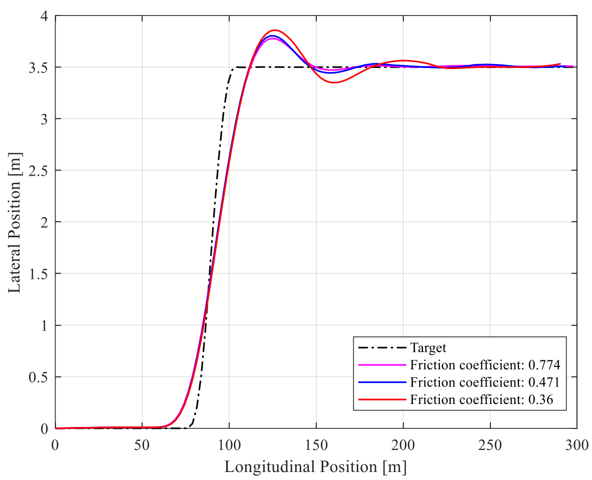

Figure 8: Tractor trajectories with different tire/road friction coefficients.

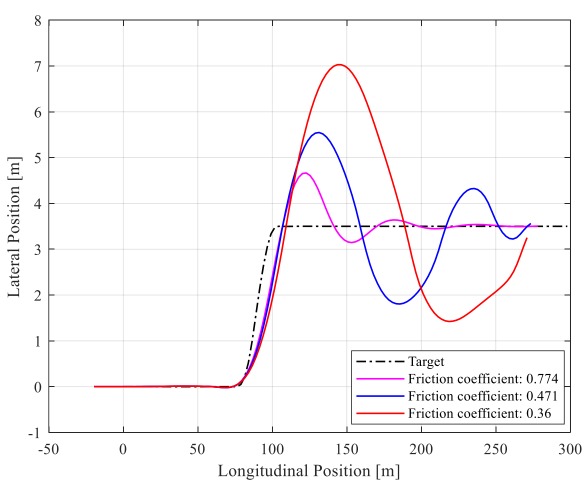

Figure 9: Trajectories of the second trailer with different tire/road friction coefficients.

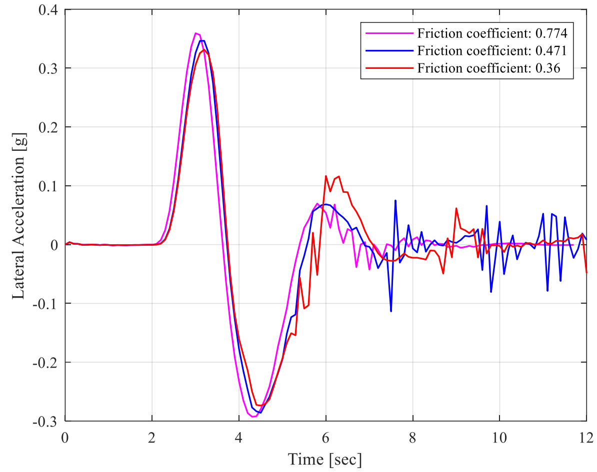

Figure 10: Tractor lateral accelerations with different tire/road friction coefficients.

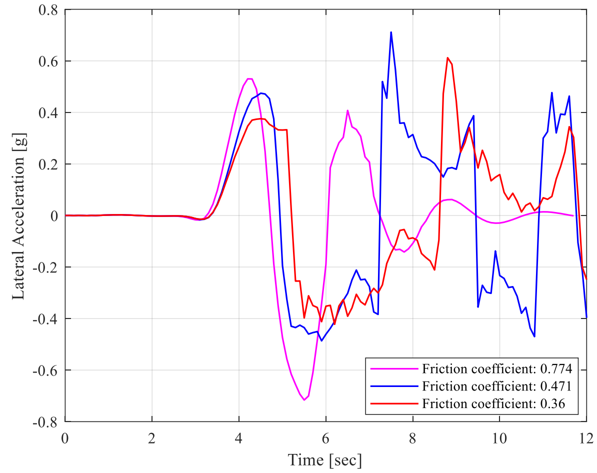

Figure 11: Lateral accelerations of the second trailer with different tire/road friction coefficients.

IV. CONCLUSIONS

This paper proposes a Monte Carlo based stochastic modeling method of varying operating conditions and vehicle parameter uncertainties for evaluating the high-speed lateral stability of AHVs and, in particular, LCVs. The Python-MatLab/SimuLink-TruckSim co-simulation simulation platform is developed to implement and examine the effectiveness of the proposed stochastic modeling method. The paper presents the selected co-simulation results of a B-train double under varying tire/road friction coefficient and vehicle forward-speed, as well as in the presence of vehicle parameter uncertainties in payload and CG height of trailers. The effects of tire/road friction coefficient on the lateral dynamics of the LCV have been evaluated and insightful findings are disclosed. The achieved simulation results on the effects of vehicle parameter uncertainties on the lateral stability of LCVs are consistent with those published in the literature. The proposed stochastic modeling method and attained results may contribute to the development of advanced active safety systems for AHVs. For instance, a numerical model of machine-learning neural network could be built based on the generated testing results, which saves the effort and costs of conducting a full matrix of testing. The proposed platform could also be used to test advanced controller by using closed-loop simulation. By applying this platform, edge conditions of both system instability and controller effectiveness could be effectively identified.

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