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Verification of a 3-degree-of-freedom bus handling model due to steering wheel input

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Abstract
This paper discusses about the development and modeling of a 3-DOF (Degrees of Freedom) bus handling model in response to steering wheel input from the driver. It includes all the relevant mathematical equations. The handling model was created using MATLAB/Simulink, incorporating parameters from TruckSim data to accurately represent the bus. The simulation results were verified by comparing them with TruckSim responses from two test procedures namely double lane change and single lane change tests. The comparison focuses on trends, magnitudes and percentage differences between the developed model and TruckSim results. In the double-lane change test, the largest percentage difference observed was 7%, while the smallest was 0.5% for yaw rate and longitudinal acceleration, respectively. In the single-lane change test, the largest percentage difference was 7.27% for lateral acceleration, and the smallest was 1.5% for yaw rate. The verification indicates that the simulation model closely aligns with TruckSim trends and can be effectively used for further study bus dynamics in various scenarios.

Keywords:
Bus handling model
Lateral acceleration;
TruckSim;
Yaw angle;
Yaw rate;

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INTRODUCTION

In recent years, high-deck vehicles such as buses are very important transportation in the economy of modern society. The bus possesses several advantages, such as the fact that buses can carry many passengers at once, making them an efficient mode of mass transit. This helps reduce the number of individual vehicles on the road, alleviating traffic congestion and lowering overall fuel consumption as stated in the previous study by [1, 2, 3]. Buses are also cost-effective for both users and municipalities. They require less infrastructure investment than rail systems and offer flexible routing that can be adjusted based on demand [4, 5, 6, 7]. Unfortunately, from the report [8][9] the number of accidents involving buses is increasing. One of the main reasons for the accident is driver error, overload, and excessive equipment malfunction. Therefore, a handling bus model has been developed to study the dynamic response of buses to steering wheel inputs and to address the critical factors influencing bus safety. This model aims to simulate various driving scenarios and predict the vehicle's behaviour under different conditions.

Three primary responses can be measured: longitudinal, lateral, and yaw motions of the bus during travel. Generally, as noted by Yu et al. and others [10, 11, 12, 13], bus models are typically developed to analyze lateral and longitudinal motions. These models aim to predict the vehicle's behaviour under various driving conditions, considering both the side-to-side (lateral) and front-to-back (longitudinal) dynamics. In the lateral direction, vehicle responses during travel are critically influenced by the steering input from the driver as stated in the previous study by Mohd Yussof et al., [14, 15, 16]. Accurate modeling of these responses is essential for understanding how buses handle turns, lane changes, and other maneuvers which are crucial for ensuring passenger safety and vehicle stability. For instance, previous research by Tunay et al., [17][18] has demonstrated that steering inputs significantly affect lateral acceleration, yaw rate, and roll angle, which are key indicators of vehicle handling performance. Understanding these dynamics helps design safer buses and improve driver training programs to mitigate the risk of accidents caused by improper handling.

In this study, the vehicle's throttle input is kept constant, and no braking input is applied. The analysis of the bus's performance focuses on the vehicle's lateral dynamics in response to steering input. Specifically, lateral dynamics tests, such as single-lane and double-lane changes, are used to assess the vehicle's travel condition. A 3-DOF (Degrees of Freedom) bus vehicle model is developed, taking into account longitudinal, lateral, and yaw motions. The output of the bus vehicle model is determined by its yaw rate, longitudinal acceleration, and lateral acceleration. Any responses that occur in other directions are neglected because this paper only focuses on the lateral motion of the model. This paper is organized into several sections, beginning with the introduction and reviewing related work. Next, the development of the bus vehicle model is then detailed, followed by the verification process. The final section presents the conclusions of the overall work.

METHOD

Modeling of the 3-Dof Bus Model

Figure 1 shows a simplified model of a bus's vehicle dynamics system with 3 degrees of freedom (3-DOF), focusing on longitudinal, lateral, and yaw motions. In the side view diagram, several forces are depicted. F_{x1} and F_{x2} are longitudinal forces on the front and rear axles while F_{z1} and F_{z2} are vertical forces on the axles, reflecting the load carried by each axle, which is influenced by the bus's weight distribution and dynamic loading conditions, such as passenger movement or braking. The center of mass, marked by a black dot, experiences a gravitational force labeled mg. Additionally, a_x is the longitudinal force at the center of mass, impacting the bus's lateral stability and handling during maneuvers.

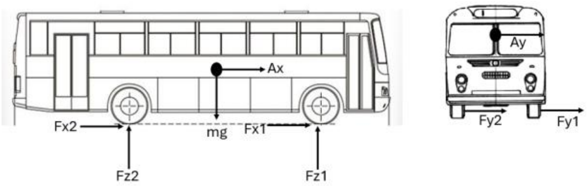


Figure 1. Side and front view of the bus model [19][20]

In the front view diagram, F_{y1} and F_{y2} are lateral forces acting on the front and rear wheels, respectively. These forces are critical for understanding the side-slip behavior and lateral stability of the bus during cornering or evasive maneuvers. The lateral acceleration, shown as a_y, is experienced at the center of mass and affects how the bus responds to steering inputs and lateral forces. Then, the handling model shown in Figure 2 is a free-body diagram of the bus model that travels on a flat, straight road at a constant speed with various maneuver controls. The parameters of the bus used in this study, including the bus dimensions and steering input during manoeuvring were collected from TruckSim data.

The 3-DOF bus handling model represents the vehicle's motions in the longitudinal, lateral, and yaw directions along the *x, y,* and *z* axes (Mohd Yussof et al., 2020) [14][16]. The model is designed to simulate the vehicle traveling on a flat, unsloped road at a constant speed. In this scenario, several factors are considered: the vehicle's sprung mass moment of inertia I_{CG} about the z-axis, the longitudinal motion with acceleration a_x, and the lateral motion with acceleration a_y. The model also accounts for the vehicle's yaw motion around the *z*-axis, characterized by the yaw angle.

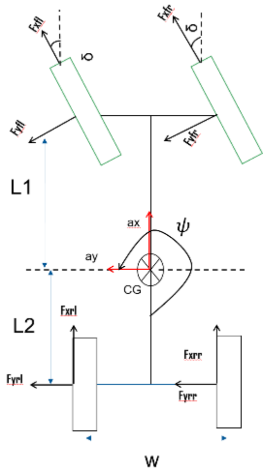


Figure 2. Handling model for bus [11, 12, 13, 14]

Additionally, the model includes the vehicle's width, w and the location of the centre of gravity. The centre of gravity is positioned at distances L_1 and L_2 from the front and rear axles, respectively. By capturing these dynamics and physical dimensions, the model provides critical insights into the vehicle's stability and control during different maneuvers. The summations of total forces acting in these directions are considered in this model to obtain the lateral and longitudinal accelerations. The total longitudinal forces acting at the front and rear of the bus include the sum of the normal forces and drag forces. These forces are essential to accurately capture the vehicle's response to various driving conditions and steering inputs [21][22]. By considering these forces, the model provides critical insights into the vehicle's stability and control during different maneuvers. Therefore, from the previous study by [14][15] the total longitudinal force acting on the *x*-axis can be written as (1).

$$\sum F_x = ma_x$$

$$\begin{aligned} F_{xrr} + F_{xrl} + F_{xfl}\cos\delta - F_{yfl}\sin\delta \\ + F_{xfr}\cos\delta - F_{yfr}\sin\delta \\ - mg\sin\theta = ma_x \end{aligned} \quad (1)$$

Meanwhile, the total lateral force acting on the *y*-axis can be written as (2).

$$\sum F_y = ma_y$$

$$\begin{aligned} F_{yrr} + F_{yrl} + F_{xfl}\cos\delta + F_{xfr}\sin\delta \\ + F_{yfl}\cos\delta - F_{yfr}\sin\delta \\ = ma_y \end{aligned} \quad (2)$$

The yaw angular acceleration $\ddot{\psi}$ is also dependent on the longitudinal and lateral forces, F_{xfl}, F_{xfr}, F_{xrl}, F_{xrr} and F_{yfl}, F_{yfr}, F_{yrl}, F_{yrr}, which act on each of the front and rear tires. By considering these forces, the yaw rate equation can be written as (3).

$$\sum M_z = I_{CG}\ddot{\psi}$$

$$\begin{aligned} \sum M_{zij} + [F_{yrr} + F_{yrl}]L_2 + [F_{xfl}\sin\delta \\ + F_{yfl}\cos\delta + F_{xfr}\sin\delta \\ + F_{yfr}\cos\delta]L_1 \\ + [F_{xfr}\cos\delta - F_{xfl}\cos\delta \\ + F_{yfl}\sin\delta - F_{yfr}\sin\delta \\ - F_{xrl} + F_{xrr}]\frac{w}{2} = I_{CG}\ddot{\psi} \end{aligned} \quad (3)$$

Then, the mathematical model of bus handling has been developed in the MATLAB/Simulink as shown in Figure 3. This model simulates the lateral and longitudinal dynamics of a bus, which includes aspects such as yaw rate, yaw angle, lateral and longitudinal accelerations, a_y and a_x as key outputs [23][24]. The model receives various inputs, such as steering angle, δ and F_{xfl}, F_{xfr}, F_{xrl}, F_{xrr} and F_{yfl}, F_{yfr}, F_{yrl}, F_{yrr}, acting as external forces, representing the dynamic interaction between the bus and its environment.

RESULTS AND DISCUSSION

The handling bus simulation model that was developed using MATLAB/Simulink, was compared with TruckSim data, as illustrated in Figure 4 and Figure 5. The simulation was conducted for two scenarios namely a single lane change and a double lane change with the bus traveling at a constant speed of 60 km/h. All bus parameters used in the simulation were taken from TruckSim data, as detailed in Table 1.

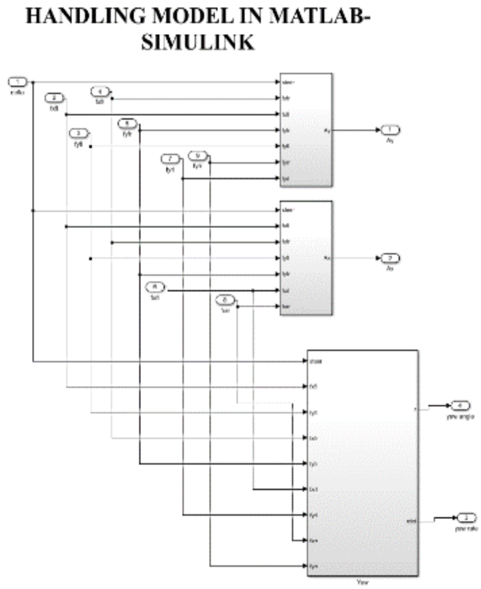


Figure 3. Development of the 3-DOF bus handling model in MATLAB/Simulink

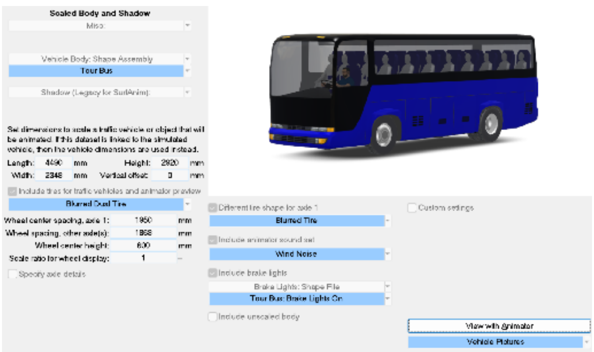


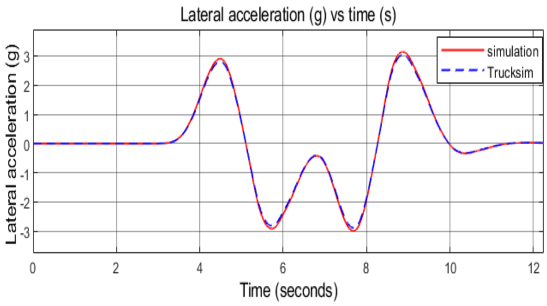
Figure 4. TruckSim setup

Figure 5. Collecting data from TruckSim

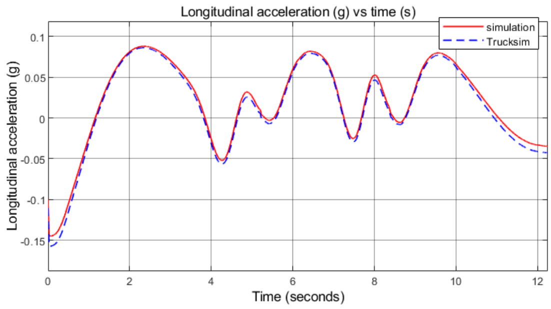
Table 1. Parameters of the Bus

Parameters	Value
m	6360kg
I_{CG}	30782.4$kg.m^2$
L_1	1.9m
L_2	3.1m
w	2.35m

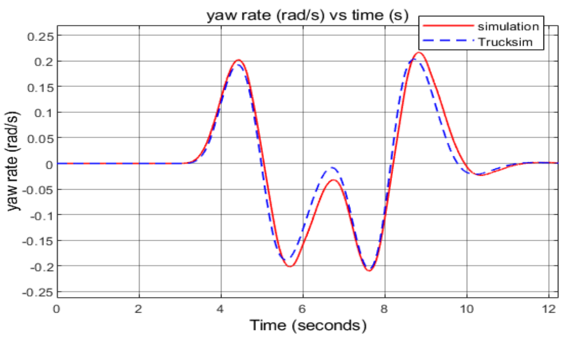
Figure 6(a) and Figure 6(b) present the results of the vehicle simulation, comparing the mathematical model with TruckSim data for the double lane change scenario at 60 km/h. The lateral and longitudinal acceleration results from the simulation follow the same trend as those from TruckSim. During the initial 3.5 seconds, the lateral acceleration is 0 g due to the absence of steering input. The maximum lateral acceleration observed is 2.8 g, while the maximum longitudinal acceleration is 0.0058 g. The percentage differences in longitudinal and lateral acceleration compared to TruckSim are approximately 0.5% and 3.62%, respectively. Next, Figure 6(c) and Figure 6(d) show the results for lateral motion, yaw rate, and yaw angle during the double lane change scenario at 60 km/h. The simulation results exhibit a similar cyclic pattern to TruckSim data. For yaw angle and yaw rate, the percentage errors between TruckSim and the simulation are 6.99% and 4.56%, respectively.



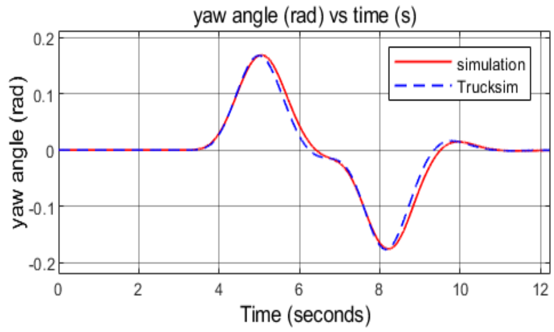
(a) Lateral acceleration for DLC



(b) Longitudinal acceleration for DLC



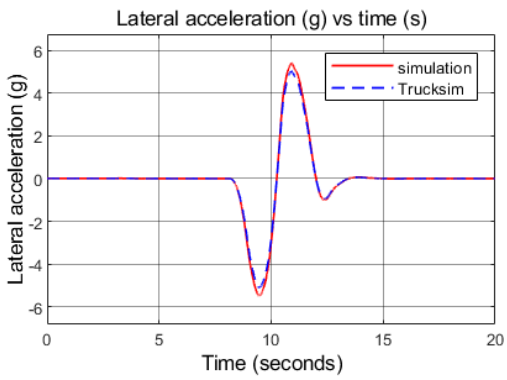
(c) Yaw rate for DLC



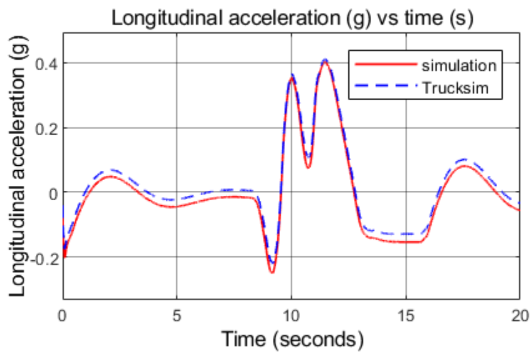
(d) Yaw angle for DLC

Figure 6. (a) to (d): Bus performances in double lane change at 60 km/h

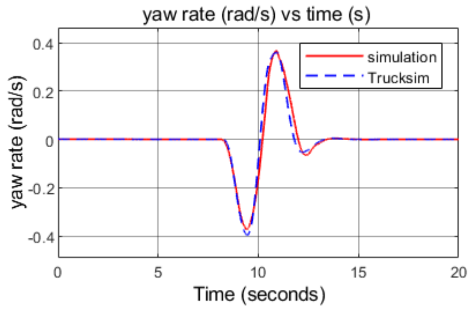
From the observations in Figure 7(a) through Figure (d), it is evident that the results from the handling model exhibit a trend similar to that of the TruckSim data. Overall, the bus performance during single-lane changes shows less than a 10% error compared to TruckSim data. Among the results, lateral acceleration exhibits the highest error at 7.27%, while the yaw rate has the lowest error at 1.5%. For longitudinal acceleration and yaw angle, the errors are 1.98% and 5.29%, respectively. Comparison of the simulated bus model with the TruckSim data revealed that the root mean square (RMS) percentage errors were minimal. The percentage error between the simulation and TruckSim data was negligible, with the maximum RMS error remaining below 10%. RMS analysis was conducted to evaluate the percentage errors for both the simulation and TruckSim models. Table 2 shows a comparison of RMS errors between the simulation model and the TruckSim outcomes for each scenario.



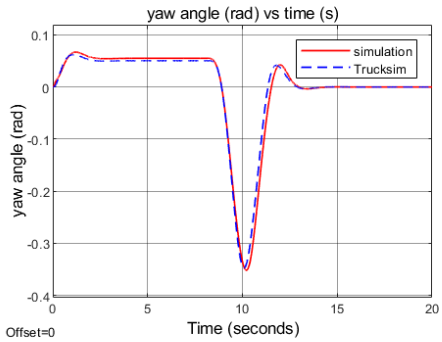
(a) Lateral acceleration for SLC



(b) Longitudinal acceleration for SLC



(c) Yaw rate for SLC



Yaw angle for SLC

Figure 7. (a) to (d): Bus performances in single lane change at 60 km/h

Table 2. The RMS Percentage Difference on Double Lane Change and Single Lane Change

Test Procedure		Speed (km/h)	Root Mean Square (RMS)		Percentage difference (%)
			Simulation	TruckSim	
DLC	a_y	60	1.4398	1.3894	3.62
	a_x		0.0564	0.0561	0.50
	$\dot{\psi}$		0.0998	0.0933	7.00
	ψ		0.0712	0.0681	4.56
SLC	a_y		1.2757	1.1893	7.27
	a_x		0.1061	0.1041	1.98
	$\dot{\psi}$		0.0852	0.0865	1.50
	ψ		0.09	0.0855	5.29

Based on the simulation results using TruckSim software, an analysis was conducted on the Root Mean Square (RMS) values for the lateral (a_y) and longitudinal (a_x) acceleration components in two types of maneuvers, namely Double Lane Change (DLC) and Single Lane Change (SLC) at a speed of 60 km/h. The results show that in the DLC maneuver, the RMS value for ay was 1.4398 in the simulation and 1.3894 in the reference data, resulting in a percentage difference of 3.62%. Meanwhile, for the ax component in DLC, there were three RMS values showing differences of 0.50%, 7.00%, and 4.56%. This indicates that the simulation model is quite accurate in representing longitudinal response, although there is a slight variation between maneuver segments.

In the SLC maneuver, the RMS value for ay showed a percentage difference of 7.27%, slightly higher than in the DLC, which may indicate that the simulation in SLC produces more significant lateral deviation from the reference data. For the ax component in SLC, the percentage difference values are 1.98%, 1.50%, and 5.29%, which are still within acceptable tolerance limits. Overall, these results indicate that the TruckSim simulation model has good representational capability for vehicle dynamics in both dual-lane and single-lane maneuver testing scenarios [25]. The relatively small percentage difference values for most components demonstrate the model's validity in the context of vehicle dynamics studies.

CONCLUSION

In this study, a handling model for a high-deck vehicle, specifically a bus, was developed and validated using TruckSim data under various conditions. The simulation results demonstrate good agreement with TruckSim data, with RMS differences of less than 10%. In the double-lane change test, the largest percentage difference observed was 7%, while the smallest was 0.5% for yaw rate and longitudinal acceleration, respectively. In the single-lane change test, the largest percentage difference was 7.27% for lateral acceleration, and the smallest was 1.5% for yaw rate. These results indicate that the 3 DOF truck vehicle model and TruckSim exhibit similar responses. Additionally, the developed model closely follows the benchmark responses provided by TruckSim

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