Design of Electronic Stability Control (ESC) Systems for Car-trailer Combinations

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Abstract— This paper presents the design of an electronic stability control (ESC) system based on trailer differential braking for increasing safety and improving handling performance of car-trailer combinations. Numerical simulations were performed using CarSim software to assess the performance of the proposed control strategies of the ESC system. To validate the virtual design of the ESC system for car-trailer combinations, a small scaled physical prototype (1:10) of a car-trailer combination was fabricated and tested. The prototype consists of an aluminum frame, accelerometer, and two wheels equipped with an electromagnetic differential braking actuator. Numerical simulation and prototype testing demonstrated the effectiveness of the proposed ESC system for car-trailer combinations.

Keywords: electronic stability control; lateral acceleration; differential braking; car-trailer combination

I. INTRODUCTION

Car-trailers are increasingly used recently for several reasons, such as, low cost, availability, and simplicity of the design. However, trailer safety systems and technologies are outdated and not increasing at the same rate as passenger vehicles. For example, in Ontario, towing a trailer with a gross vehicle weight of up to 4,600 kilograms does not require a higher class driving license. In addition, the Ministry of Transportation of Ontario does not have any regulation regarding braking systems required to ensure the safety of trailers [1].

Car-trailers usually face two of the most dangerous scenarios, known as trailer sway and jackknifing [2]. In addition, rollovers have a huge impact on car-trailers' safety. Rollovers occur due to different reasons, such as, high speeds, crosswinds, road conditions, and center of gravity of trailer.

Understanding the dynamic features of trailer sway, jackknifing and rollovers will facilitate the design and development of robust ESC systems. First, trailer sway is a dynamic phenomenon that the trailer conducts an angular oscillation around the hitch. Essentially, trailer sway results from small yaw damping ratio of the trailer. Once the car-trailer travels on straight line at a critical speed, the corresponding yaw damping ratio is equal to zero. Above the critical speed, the car-trailer will lose lateral stability due to the increasing amplitude of the angular oscillation [3]. Vehicle system parameters, such as, trailer payload, mass moment of inertia, distance between hitch and trailer axle, tire cornering stiffness coefficients, etc., impose significant impacts on the yaw damping ratio. Due to a small yaw damping ratio, external disturbances, e.g., crosswind, may make the trailer lose traction and gripping the road, which causes the trailer to swing and skid [4].

Articulated vehicles, such as car-trailers, exhibit a unique dynamic feature, which is known as rearward amplification. The rearmost trailer usually has larger lateral motions than the tractor; the trailer may be the first unit to rollover; by the time the driver realizes what is happing, it is too late to take a corrective action. Rollover threshold value is generally expressed in terms of a lateral acceleration value. Car-trailer rollover frequently occurs over sharp turns at high speeds and under evasive maneuvers.

Jackknifing is the third major unstable motion mode. The relative braking force distribution between car and trailer imposes the most significant impact on the occurrence of Jackknifing. If a larger braking force is allocated to the rear axle of the car, under a curve negiation with heavy braking, Jackknifing occurs frequently. Moreover, external distrubances, such as corsswind, may also cause Jackknifing [5].

To address the aforementioned problems and avoid severe accidents, conventional braking systems may be enhanced by introducing active trailer differential braking systems. An electronic stability control (ESC) system has been developed as an important safety feature in passenger vehicles. ESC is an active safety technology that improves the vehicle's stability by assisting the driver to keep the car-trailer combination on the desired path [6].

To implement the functionality of ESC, several vehicle dynamic states can be controlled, such as yaw rate of vehicle units [7], lateral motions of vehicle units [8], and later accelerations of vehicle units. Each of the above mentioned methods requires a car-trailer combination equipped with several sensors to ensure a responsive and robust system.

Lateral acceleration control is proposed for the design of active trailer differential braking systems. A small-scale prototype is fabricated and examined to validate the active trailer differential braking system designed in this project, and the lateral-acceleration rearward amplification (RWA) is used to as an essential lateral stability measure of the car-trailer combination [9]. Controlling the lateral acceleration of the vehicle units may effectively prevent the occurrence of rearward amplification, in which the trailer has a greater lateral acceleration than the leading unit, which can lead to rollover of the trailer [10].

II. DESIGN OF AN ACTIVE TRAILER DIFFERENIAL BRAKING SYSTEM

The design of the electronic stability control (ESC) system involves the modeling of the car-trailer system for controller design, a small-scaled physical prototype fabrication, and performance evaluation. The design process is divided into two different phases. The first is the design of a virtual prototype, while the second phase is the fabrication of the small-scaled physical prototype to validate the virtual design.

A. Mathematical Modeling [11]

As seen in Fig 1, a yaw-plane car-trailer model with 3 degrees of freedom (DOF) is generated for the ESC controller design.

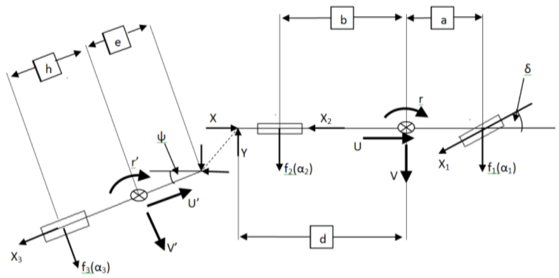

Figure 1. Schematic representation of the 3 DOF yaw-plane car-trailer model and the parameters used.

The equations of motion of the car are expressed as follows:

$$m_1(\dot{U} - Vr) = -X_1 \cos\delta - X_2 + X \quad (1)$$

$$m_1(\dot{V} + Ur) = f_1(\alpha_1) + f_2(\alpha_2) + X_1 \sin\delta - Y \quad (2)$$

$$I_1\dot{r} = af_1(\alpha_1) - bf_2(\alpha_2) + aX_1 \sin\delta + dY \quad (3)$$

The trailer's equations of motion are cast as:

$$m_2(\dot{U}' - V'r') = -X_3 - Y\sin\psi - X\cos\psi \quad (4)$$

$$m_2(\dot{V}' + U'r') = f_3(\alpha_3) + Y\cos\psi - X\sin\psi \quad (5)$$

$$I_2\dot{r}' = -hf_3(\alpha_3) - e(-Y\cos\psi + X\sin\psi) \quad (6)$$

Due to the fact that the trailer is connected to the leading vehicle with an articulated joint, the forward velocity and acceleration of the leading and trailing units are assumed the same. This assumption simplifies the trailer equations of motion and helps linearize them.

In addition, the articulation angle ψ is approximated to be small, which leads to:

$$\cos(\psi) = 1 \quad (7)$$

$$\sin(\psi) = \psi \quad (8)$$

Also, the following equation is determined at zero initial conditions.

$$\dot{\psi} = r - r' \quad (9)$$

Using all the above assumptions and approximations, the linearized equations of motion can be expressed as:

$$\boldsymbol{M}\{\dot{x}\} + \boldsymbol{D}\{x\} + \boldsymbol{F}\delta = 0 \quad (10)$$

where the state variables are written as [11]:

$$\{x\} = \{V\ r\ \dot{\psi}\ \psi\} \quad (11)$$

Matrices M, D and F are listed in Appendix A.

The parameters listed in Table 1 are used in the mathematical modeling and the CarSim model generation.

TABLE I. PARAMETERS USED TO DESIGN AND TEST A VIRTUAL PROTOTYPE.

Parameters		
Description	***Symbol***	***Value***
Leading vehicle mass	M_L	1521 Kg
Trailer mass	M_T	602 Kg
Distance between CG and front axle	a	0.972 m
Distance between CG and rear axle	b	1.807 m
Distance between vehicle CG and contact point with the trailer	d	4.835 m
Distance between the trailer CG and contact point with the vehicle	e	2.00 m
Distance between the CG and the rear axle	h	0.6 m
Height of vehicle CG	$H1_{CG}$	0.325 m
Height of trailer CG	$H2_{CG}$	0.676 m
Steering angle	δ	
Longitudinal forces of car front wheels, rear wheels and trailer wheels, respectively	$X_{1,2,3}$	
Car and trailer forward velocity	U,U'	
Lateral velocity of car and trailer, respectivly	V,V'	
Lateral forces of car front wheels, rear wheels and trailer wheels, respectively	$f_{1,2,3}$	
Car, trailer yaw angle, respectively	r,r'	
Articulation angle	ψ	

Equations (1) to (11) show how to generate a mathematical model of a car-trailer combination with some assumptions to linearize the system. To introduce a trailer differential braking system for generating a counter moment to stabilize the car-trailer combination [10], Equation (6) should be modified as:

$$I_2\dot{r}' = -hf_3(\alpha_3) - e(-Y\cos\psi + X\sin\psi) + \Delta M_z \quad (12)$$

Using the same approximations and assumptions, the governing equations of motion of the car-trailer can be linearized and simplified as the following form:

$$M\{\dot{x}\} + D\{x\} + C_B u + F\delta = 0 \tag{13}$$

where,

$$u = -K_p * a'_y \tag{14}$$

The lateral acceleration of the trailer (a'_y) can be formulated using mathematical manipulations and operations. In this research, an accelerometer sensor is used to measure the lateral acceleration of the physical prototype.

B. *ESC Controller Design*

There are several types of control techniques that can be used to design an ESC system, such as PID and LQR [12]. The objective of this research is not only to design an ESC controller, but also to fabricate a small-scaled car-trailer prototype equipped with the ESC system. Thus, a feasible ESC controller is designed. A P-control scheme is used for the simplicity of tuning, proving the concept design, and fabricating a small-scaled car-trailer prototype with the ESC.

The block diagram of the controller design is shown in Fig. 2, representing the P-control scheme.

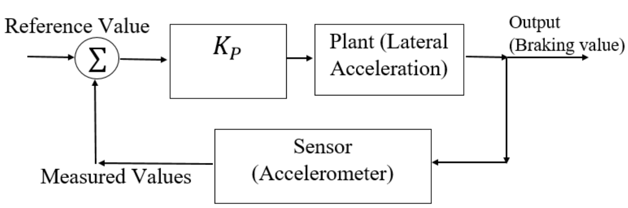

Figure 2. Block diagram representation of the designed system with a P-controller.

C. *Virtual Car-Trailer Prototype with the ESC system*

The virtual car-trailer prototype with the ESC system is designed and tested using CarSim software package. CarSim provides various vehicle and trailer models that could be used to simulate selected testing maneuvers.

Since the trailer is the focus of the research, the ESC controller designed in Matlab is combining with the car-trailer model developed in CarSim. The designed ESC is built upon the existing Anti-Locking Braking System (ABS) of trailers. The ESC controls the right and left brakes of the trailer independently. This is known as differential braking [13]. Differential braking is used to control the yaw moment, which affects the lateral and yaw motions of the trailer.

To ensure that the ESC is functioning as desired, several testing maneuvers are simulated, such as a double lane change maneuver.

Fig. 3 shows the integration of the ESC controller designed in Matlab/Simulink software and the car-trailer model generated in CarSim software.

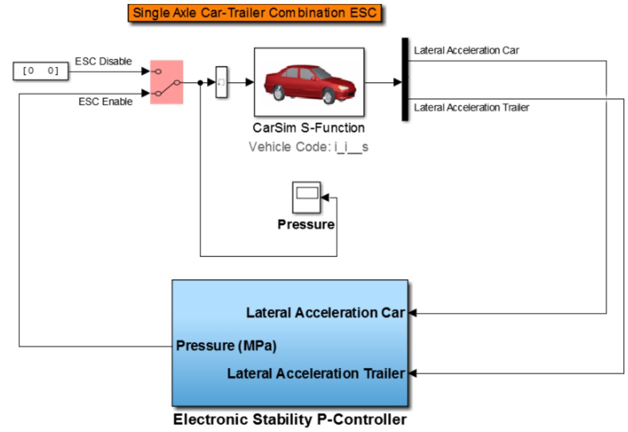

Figure 3. CarSim model of the Car-trailer combination.

The car-trailer block shown in Fig. 3 exports the lateral acceleration of the leading vehicle and the trailer to the P-Controller based ESC system. The controller multiplies the input by the gain K_p, and then a generated brake pressure value is sent back to the car-trailer block to apply brakes on a specific wheel. This process continues until the error between the desired and actual lateral accelerations is minimized. The ESC controller is designed to meet the requirements of a differential braking where brakes are applied on each wheel independently. In addition, the controller applies braking force in the form of brake pulsing to prevent wheels from locking.

D. *Small-Scaled Physical Car-Trailer Prototype with the ESC System*

Once all the results are justified based on the numerical simulation results of the virtual car-trailer prototype with the ESC system, a 1:10 small-scaled physical car-trailer prototype with the ESC system is designed and fabricated. The purpose of building the physical prototype is to conduct similar tests that have done in CarSim and to compare the performance measures derived from both cases.

Since the physical prototype is equipped with a P-controller, a microcontroller is installed on board. An Arduino Uno is used as the brain of the module to simulate all the data gathered by the accelerometer. The designed ESC is stored in the microcontroller to apply the required braking force based on the input of the lateral acceleration. In addition, the fabricated trailer is equipped with differential braking actuator using two electromagnetic brakes. Fig. 4, shows the fabricated prototype with all the mentioned components needed to achieve a functional ESC.

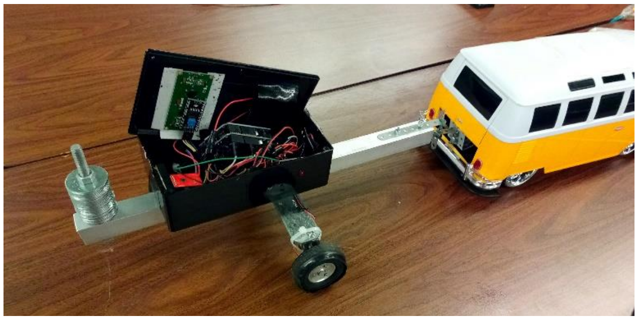

Figure 4. The fabricated 1:10 small scale prototype for testing the functionality of the ESC controller.

III. RESULTS AND DISCUSSION

As mentioned earlier, the car-trailer model developed in CarSim is used to simulate the double lane change maneuver to test the effectiveness of the designed ESC. A representation of double lane change maneuver is shown in Fig. 5.

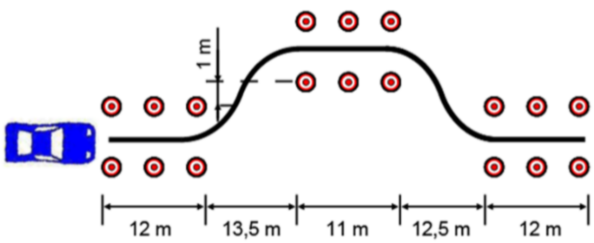

Figure 5. A representation of a double lane change maneuver [14].

The first test is done using the combination of a car towing a trailer, which is not equipped with the ESC. The Fig. 6 shows the time histories of the lateral acceleration of the vehicle units.

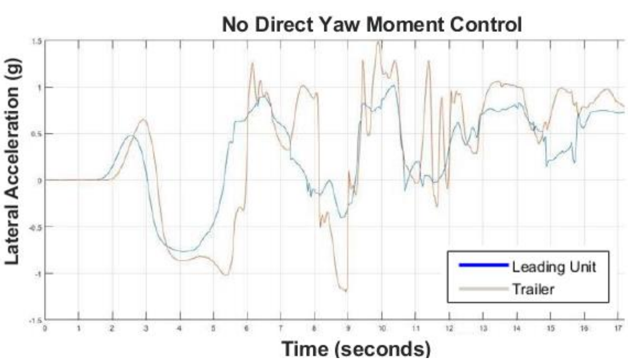

Figure 6. Graph generated from CarSim, representing the behavior of the car-trailer combination when ESC is OFF.

By looking at the graph in Fig. 6, the blue line represents the lateral acceleration of the leading vehicle, which gets affected by the trailer in similar scenarios, such as double lane change maneuver, whereas the orange line represents the lateral acceleration of the trailer. It is observed that the trailer's reaction has a time delay and then the combination lost stability. In addition, it is also observed that the trailer exhibits a higher lateral acceleration over the maneuver, which means that the trailer has a larger lateral motions than the leading car, which results in losing control over the combination.

To examine the car-trailer with the ESC, the same test is carried out. The ESC is added to the trailer. Fig. 7 represents the time histories of the lateral acceleration of the leading vehicle and trailer with the ESC controller under the maneuver.

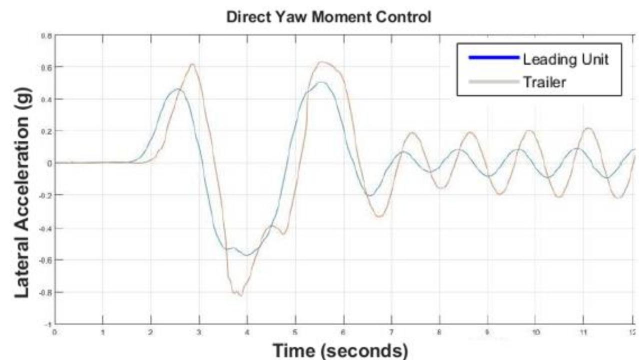

Figure 7. Graph generated from CarSim, representing the behavior of the car-trailer combination when ESC is ON.

By looking at the curves in Fig. 7, the blue curve represents the response of the leading vehicle, where the orange curve represents the trailer's behavior. It is observed that the combination has its lateral acceleration peaks at the turning points. As expected, the trailer has a larger lateral acceleration compared to the leading vehicle. However, the combination does not lose stability and the sway is controlled. By looking at the curves between time intervals of 7-18 seconds, the combination has a minor oscillation, and this is due to the use of P-controller.

By comparing the behaviors of the controlled and uncontrolled combination, we conclude that the trailer's lateral acceleration has an impact on the leading vehicle as it loses stability in the first case, where the trailer loses stability. In addition, the lateral acceleration of leading vehicle and trailer have a larger amplitude when the combination is not equipped with the controller.

As stated previously, the testing phase for the physical prototype defers from the virtual prototype. To compare the results of the virtual and physical prototype, two tests have been conducted using the physical prototype. Both tests have the same scenario where the vehicle would accelerate to a certain speed using a treadmill until it loses stability. To exert graphs from the physical prototype, a gyroscope is used to calculate the articulation angle between the leading vehicle and the trailer with reference to the leading car. Fig. 8 shows the representation of the articulation angles over time in both the controlled and uncontrolled situations based on the testing results using the small-scaled physical car-trailer prototype.

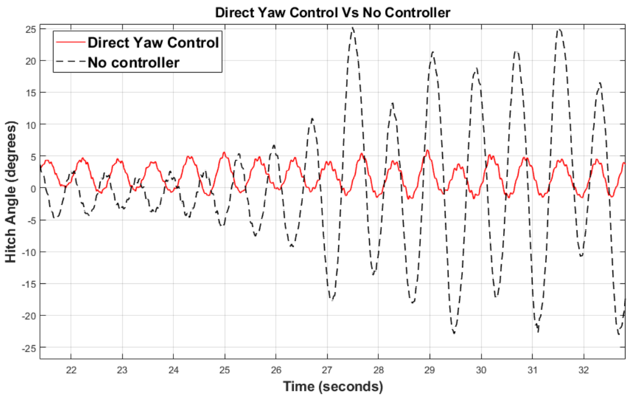

Figure 8. Comparison between the responses of the controlled and uncontrolled car-trailer combination based on the test with the small-scaled car-trailer prototype.

IV. CONCLUSIONS

An active trailer differential braking controller is designed using the P-control technique based on a 3-DOF yaw-plane car-trailer model. The ESC controller designed in Matlab is then integrated with the car-trailer model generated in CarSim for co-simulation. Built upon the virtual car-trailer with the ESC, a 1:10 small-scaled physical car-trailer prototype with the ESC is fabricated. In both virtual and physical prototype tests, the ESC improves the stability by controlling the yaw moment of the combination. Although the results based on the P-control scheme are promising, an advanced control scheme for the ESC could be used to further improve the performance of the ESC. Since the project is carried out under limited resources and time, there is room to improve in a few aspects, such as building a 1:10 small-scaled car-trailer prototype and implementing an advanced control strategy for the ESC.

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APPENDIX A

$$M = \begin{bmatrix} m_1 + m_2 & -m_2 d & -m2_e & 0 \\ -m_2 d & I_1 + m_2 d^2 & m_2 ed & 0 \\ -m_2 e & m_2 ed & I_2 + m_2 e^2 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \text{(A.1)}$$

$$F = \begin{bmatrix} c_1 \\ c_1 a \\ 0 \\ 0 \end{bmatrix} \quad \text{(A.2)}$$

(A.3)

$$D = \frac{1}{u} \times \begin{bmatrix} -c_1 - c_2 - c_3 & -c_1 a + c_2 b + c_3 d + (m_1 + m_2) u^2 & c_3 (h+e) & -c_{3u} \\ -c_1 a + c_2 b + c_3 d & -c_1 a^2 - c_2 b^2 - c_3 d^2 - m_2 d u^2 & -c_3 d (h+e) & c_3 du \\ c_3 (h+e) & -c_3 d (h+e) - m_2 e u^2 & -c_3 (h+e)^2 & c_3 (h+e) u \\ 0 & -u & u & 0 \end{bmatrix}$$