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Dynamic Performance of Multi-Trailer Articulated Heavy Vehicles with Advanced Control Systems

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Abstract: With the current situation of exponential growth in freightage and traffic congestion, Multi-Trailer Articulated Heavy Vehicles (MTAHVs) have become an economical and pragmatic solution to transportation. However, problems like high-speed lateral stability and low-speed maneuverability are still challenges with which MTAHVs are still facing due to high centers of gravity, multi-unit structures and large sizes. Jackknifing, rollover, and fish-tailing are three typical unstable motions that cause severe road accidents at high speeds. Steerable axles including passive and active steering systems have been recognized as a promising method to improve the dynamic performance of MTAHVs. Dynamic performance tests were conducted to compare the MTAHVs equipped with active and passive trailers steering systems against a baseline MTAHV without any steerable trailer axles installed. To examine and evaluate the capabilities of each steering system, an A-train double MTAHV with high degrees of fidelity was developed in TruckSim. Advanced driver models and passive and active steering systems were designed and implemented using MATLAB/Simulink. The baseline set was implemented with trailer and dolly axles fixed and without any steering input. Two road conditions were considered based on different tire-road friction coefficients to simulate dry and wet road surface conditions. Two typical vehicle dynamics performance test scenarios, High Speed Lane Change (HSLC) and Low Speed Turn (LST), were conducted. The simulation results showed that on good road condition, both passively and actively steered trailer axles considerably improved low speed maneuverability in comparison to fixed-axle baseline trailer axles. It was observed that the passive steering mechanism reduced the MTAHVs' high speed lateral stability while the active steering mechanism was able to significantly improve driving performance at both high and low speeds at both high and low friction road conditions.

1. Introduction

1.1. Purpose

A MTAHVs is a vehicle system consisting of a towing unit named a tractor and more than one trailing unit. Units of MTAHVs are connected with each other at articulated point with mechanical couplings like pintles, fifth wheels and dollies. As shown by the work done in [1], MTAHVs efficiently increase the cargo capacity per driver by 25% to 100% when compared with single unit vehicles and conventional tractor-semi-trailer systems. The increase transport efficiency and reduced emission rate have caused MTAHVs to emerge as an economical and pragmatic solution for transport. However, due to the fact that MTAHVs are much longer than conventional heavy vehicles (length allowed to be up to 40 meters in Ontario Canada) and multi-unit dynamic performance is much more complex, MTAHVs are still facing problems in both high and low speed driving scenarios. As illustrated in a previous research [2], at high speed, MTAHVs' high centre of gravity and large size lead to inferior lateral stability, where rollover, jack-knifing and trailer-sway (fishtailing) are three typical unstable motion modes. At low speed, path-following off-tracking (PFOT) becomes the nominal concern and MTAHVs exhibit poor manoeuvrability at these speeds. To compensate for the loss of high speed stability and low speed manoeuvrability, while achieving much higher transport efficiency, active trailer steering (ATS) is a potential solution and a popular research topic [3]. To validate and compare passive trailer steering system and ATS, co-simulations are conducted by combining the integrated active/passive controllers designed in MATLAB/Simulink and the nonlinear A-train double with high degree of fidelity generated in TruckSim.

1.2. Numerical Simulation

It has been widely approved that implementation of computer simulation in automotive engineering process and virtual test are valuable prior to a full-size on-site test being conducted. For example, the work done in [4] has illustrated the simulation testing ability for vehicle dynamic evaluation based on relative performance standards. Actually, in 2008, Australia Transport Commission has published a series of testing requirement for road vehicle performance [5], in which, both in-vehicle and numerical analysis are allowed and acceptable. In this study, a multibody dynamic simulation software named TruckSim was implemented to develop the MTAHV dynamic nonlinear models. The corresponding driving scenarios (HSLC and LST) were designed and developed in TruckSim as well. An advanced driver model was developed in Simulink and was linked with TruckSim via MATLAB S-function.

2. Vehicle Model

2.1. Tractor and Trailers

The specific MTAHVs model applied in this study is A-double, in which one 3-axle tractor is towing first and second trailers. As shown in Figure1, both first and second trailers have 3 axles and they are connected through a two-axle converter dolly.

Fig. 1 A-double model in TruckSim.

TruckSim simulates units in MTAHVs as sprung masses and un-sprung masses, which include tractor, 1st trailer, 2nd trailer, dolly, axles, etc. The tire models used in TruckSim are based on nonlinear magic tire formulas.

2.2. Passive Steering Mechanism

Typical passive trailer steering mechanism controls the last two axles of each trailer in an A-double while the first axle of each trailer is non-steering. The passive trailer axle steering is the rotating motion in yaw plane of the whole axle rather just wheels ("Wagon Steer") that is different from that of passenger cars. The steering command and mechanism is directly dependent on the articulated angle. For example, the steering angle of the first trailer is dependent on the articulation angle between the tractor and the first trailer and the axle steering angle of the second trailer relies on the articulation angle between the convertor dolly and the second trailer.

3. Testing Manoeuvres

3.1. High Speed Lane Change

As announced by Road Transportation Association of Canada (RTAC) [6], High Speed Lane Change (HSLC) is an equivalent testing manoeuvre simulating the vehicle dynamic performance on obstacle-avoidance at highway operating conditions. A single cycle sine wave of lateral acceleration is usually selected to generate the target path due to its symmetrical properties. As illustrated in the Figure 2, one important measurement for this scenario is the transient path-following off-tracking (PFOT), which is defined as the deviation of the path of the centre of the rearmost axle of the last trailer from the target path. In this study, the vehicle speed is constant at 85 [km/h], and the off-tracking is the lateral deviation between the trajectory of third axle centre of the 2nd trailer and the desired path. To investigate the performance of the steering systems over different road surface friction conditions, two high and low friction coefficients i.e. 0.85 and 0.35 respectively, were implemented in the simulations.

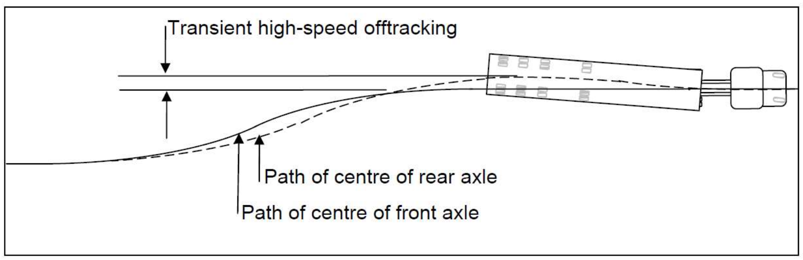

Fig. 2 High-speed lane-change and transient path-following off-tracking.

3.2. Low Speed Turn

A detailed discussion of the influence of weight, dimension and payload to the MTAHVs dynamic performance at low speed is found in the research work done in [7], which has demonstrated the limited manoeuvrability of the MTAHVs at low speed due to their long dimension and wheel bases. To describe and test the maneuverability performance, based on the standard suggested in [6], low speed turn (LST) with a constant speed as low as 20km/h is conducted in this study on both high (0.85) and low (0.35) friction road conditions. Figure 3 clearly illustrates the potential consequence of high LST off-tracking values.

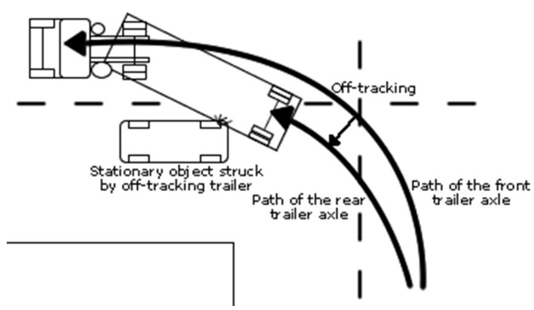

Fig. 3 Low speed turning maneuver and consequent off-tracking.

4. Simulation Results

This section presents all the simulation test results of both HSLC and LST manoeuvres at both high and low road friction conditions. The results have been classified into two sections based on the driving scenarios. All results are presented in the format of trajectories (in global X and Y coordinates) of tractor front axle centre (TFAC) and the last axle centre of 2nd trailer.

4.1. High Speed Lane Change

The first test results are presented in Figure 4, where the horizontal axis is global X-coordinates while the vertical axis is global Y-coordinates. All the baseline, passive and active trailer steering systems have been concluded with colour of red, green, and blue, respectively. Solid lines represent the path of the front axle centre of the tractor and the dashed lines represent the last axle centre of the rearmost trailer. It is shown that all three MTAHVs are performing the expected single lane change maneuver with the desired lateral displacement of 3.5 meters. Close observation of the peak value at the end of the lane-change motion is employed to define the difference between the three systems dynamics performance. It is obvious that the passive steering mechanism has increased the overshoot problem at the end of obstacle avoidance manoeuvre, and the trailer motion is higher than that of the baseline (with non-steered trailer axles). It could also be noted that the active trailer steering system (blue curves) are performing the best regarding path-following with the minimum overshoot of both tractor and rearmost trailer.

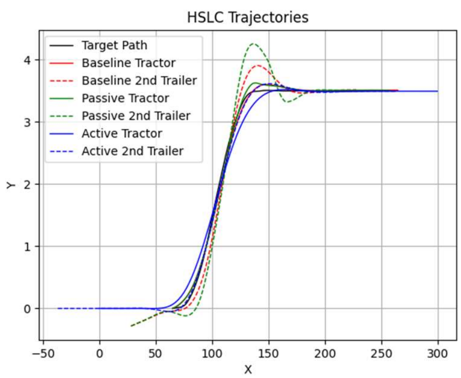

Fig. 4 HSLC testing results at high-friction road condition.

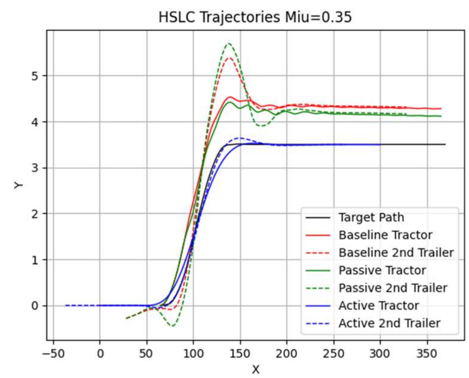

Fig. 5 HSLC testing results at low-friction road condition.

Figure 5 illustrates the trajectory of all the three MTAHVs deployed analogous to the previous test manoeuvre; however, the road friction coefficient is reduced to 0.35 to simulate slippery road condition. The closed-loop steering input to the tractor's front axle in this test is kept the same as in the HSLC with high-friction road condition. The results show severe deviation from the target path for both the baseline and passive steering mechanisms. Both baseline and passive-steering MTAHVs are drifting out of the lane width with the peak lateral offset equals to about 5.5 meters. A worse situation could be observed with the MTAHV equipped with passive steering mechanism (green curves), where both the tractor and trailer have higher peak value than that of baseline. However, ATS system successfully assisted the MTAHV in performing the single lane change manoeuvre on the slippery road condition without large over-shooting.

4.2. Low speed turn

The results for the low speed turn are shown in the same format as that of the HSLC, where both tractor and 2nd trailer path trajectories are plotted for all three MTAHVs. The result from the LST with high-friction road condition is presented in the Figure 6. One could notice that all three MTAHVs perform the expected 90-degree low speed turn, and all the tractors follow the target path without severe errors. As for the second trailer, the rearmost axle exhibits a noticeable off-tracking from the target path on all three cases. The passive steering mechanism (green curves) have effectively reduced the off-tracking by steering the last two axles of each trailer. However, ATS further reduced this off-tracking compared with the passive steering. One could notice the tail swing of the 2nd trailer before the turning motion starts, which is more considerable than the other two MTAHVs. This is inevitable in order to reduce the maximum swept path compared with the passive steering strategy during the LST. As long as the 2nd trailer doesn't violate the road limits, the resulting tail swing wouldn't cause any issue. Since passive steering mechanism control the steering angle completely based on the articulation angle, the similar outward motion is less.

The results for the low-friction road condition are shown in Figure 7, in which the difference between baseline, passive and ATS are obvious. Only the MTAHV equipped with ATS system successfully finished the 90-degree turning although the error is larger compared with high-friction LST. However, both passive and baseline MTAHVs did not achieve the expected turning motion with heading straight instead. Both passively and actively steered trailer axle systems improved the LST manoeuvrability at good road condition. The advantages of actively steered trailer axle system over the baseline and passively steered trailer axle systems in LST is especially significant at low-friction road conditions.

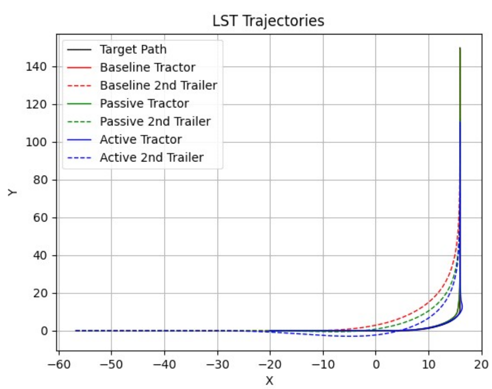

Fig. 6 LST test result at high-friction road condition.

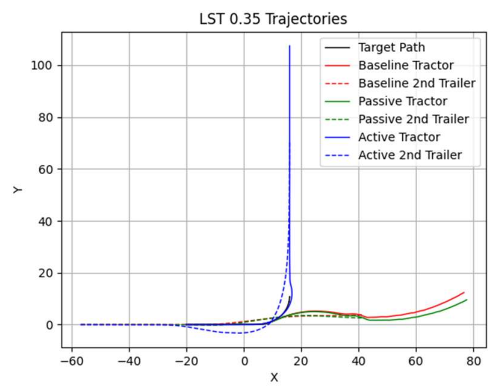

Fig. 7 LST test result at low-friction road condition.

5. Conclusion

Three MTAHV models have been developed in this study, two with active and passive steerable trailer axles and one without any steerable trailer axle. Based on the given testing standard scenarios by RTAC, a high speed lane change and low speed 90-degree turn manoeuvres were chosen to explore the dynamic features of the steerable trailer systems at various driving and road conditions.

The results have shown good improvement of MTAHV dynamic performance at low speed turn after installation of the steerable axles on the trailers with good road condition. Both passive and active steerable axles effectively reduced the off-tracking between the desired path and the last trailing unit's rearmost axle at low speeds. This improvement potentially reduces the minimum capable turning radius for MTAHVs, so collisions due to off-tracking of the trailer out of the lane width could be avoided. The improvement of active trailer steering system in LST manoeuvrability is especially significant at low-friction in comparison with passive trailer steering system and the baseline system.

Lateral stability at emergent obstacle avoidance or lane change situation at high speeds is a main concern to avoid the rollover of the system. The study showed that the passive trailer steering system reduced lateral stability at high speed which is especially significant at low-friction road condition. The MTAHV equipped with ATS showed better lateral stability at high speed lane change manoeuvre at both good and bad road friction conditions in comparison with that with passive trailer steering system and the baseline.

Due to the fact that MTAHVs effectively increase the transportation efficiency which reduces the emissions and fuel consumption, they are becoming a potential mainstream for transportation of goods. To compensate the loss of high-speed lateral stability and low-speed manoeuvrability due to large size and weight of MTAHVs, this study provide valuable information for trailer steerable axle selection regarding different types of operation conditions.

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