

## PERFORMANCE IMPROVEMENT FOR A-DOUBLE COMBINATION BY INTRODUCING A SMART DOLLY



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### Abstract

This study is focusing on how much the performance of a tractor, semitrailer, dolly and semitrailer (A-double) combination can be improved by a controlled/smart dolly which is equipped with integrated (electric/hydraulic) propulsion, steering, and braking. The aim is to achieve similar performance as the tractor-semitrailer combination which only has half of the loading capability in volume or tonnes. The results showed that performances such as startability, gradeability, rearward amplification, and yaw damping, for the A-double with smart dolly have same or similar as the tractor-semitrailer.

**Keywords:** Performance Based Characteristics, Long heavy vehicle combination, Conventional heavy vehicle combination, Smart dolly, Road safety

## 1. Introduction

From a society perspective, there will be a need for goods to be transported and distributed. According to (Åkerman I. and Jonsson R., 2007), the amount of transported goods is expected to be increased by 55% from year 2000-2020. Goods are transported on water, rail, air, and on land (roads). However, the overlapping of choosing either type of transportation is fairly small for a specific part of a transportation mission. Thus, each type of transportation type needs to minimize its environmental footprint and offer the society cost effective transports. In the case of heavy goods transported on road on longer distances than city distribution, Long Heavy Vehicle Combinations (LHVCs) are a viable option. LHVC consists of a motor vehicle, either truck or tractor, with multiple trailers. Using longer combinations instead of existing Conventional Heavy Vehicle Combinations (CHVCs) to transfer the same amount of goods results in fewer trips, less congestion, reduced fuel consumption and emissions. Due to longer length and heavier weight of LHVCs, their potential impacts on traffic safety have always been a major concern (Grislis A. 2010). Therefore, by introducing LHVCs as a major part of future transportation, there is a need to ensure that they are performing within specific boundary conditions.

Defining proper technical characteristics, denoted as Performance Based Characteristics (PBCs) (Kati M.S. 2013), for LHVCs would assist to create operational requirements by which LHVCs will be allowed to operate the road network with less negative road safety impacts. In addition introducing PBCs instead of existing traditional prospective regulation scheme results in a great space for vehicle design innovations to improve traffic safety.

The aim of this study is to see how to improve the performance of a A-double combination by using smart dolly to meet similar performance levels of a tractor-semitrailer with doubled load capacity compared with a tractor-semitrailer. The A-double combination is combination with two semitrailer connected to each other by a dolly. Here, a smart dolly is defined as a dolly which is both steerable and propelled.

## 2. Vehicle dynamic model

Figure 1 depicts the two considered combinations, a tractor-semitrailer and an A-double combination (Tractor, semitrailer, dolly and semitrailer). The total Gross Combination Mass (GCM) of the tractor-semitrailer combination is 40 tonnes and its total length is 16.5 meters while the A-double combination has a total GCM of 80 tonnes and length of 31.5 meters.

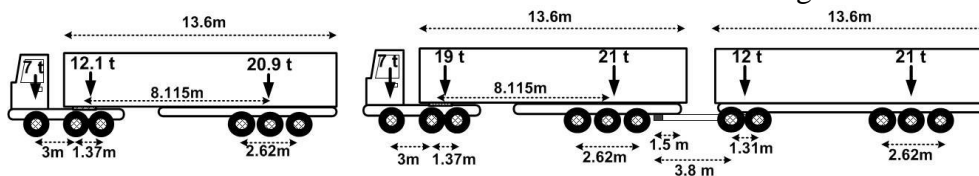


Figure 1- Tractor-semitrailer and A-double combination

The method used for the investigation is system simulation. The system model, vehicle model and driver model, is simulated for different manoeuvres in order to determine the system performance. The vehicle model used in analysing PBCs is a bicycle model has three degrees of freedom in longitudinal, lateral and yaw direction. The considered assumptions for the modeling are as follows: the combination have no bounce; the roll dynamic and suspensions are neglected. Equations of motion of the combination' units are obtained from following equations, for each unit  $j$ :

$$\begin{aligned}
\dot{V}_{x_j} &= (m_j V_{y_j} \dot{\phi}_j + \sum_{i=1}^{n_j} F_{x_{ji}} \cos(sc_{ji}\theta_j) - \sum_{i=1}^{n_j} F_{y_{ji}} \sin(sc_{ji}\theta_j) + F_{cx(j-1)} \cos(\theta_j) - F_{cy(j-1)} \sin(\theta_j) - F_{cx_j} - F_{res_j}) / m_j \\
\dot{V}_{y_j} &= (-m_j V_{x_j} \dot{\phi}_j + \sum_{i=1}^{n_j} F_{x_{ji}} \sin(sc_{ji}\theta_j) + \sum_{i=1}^{n_j} F_{y_{ji}} \cos(sc_{ji}\theta_j) + F_{cx(j-1)} \sin(\theta_j) + F_{cy(j-1)} \cos(\theta_j) - F_{cy_j}) / m_j \\
\dot{\phi}_j &= (\{\sum_{i=1}^{n_j} F_{x_{ji}} \sin(sc_{ji}\theta_j) + \sum_{i=1}^{n_j} F_{y_{ji}} \cos(sc_{ji}\theta_j)\} l_{ji} + \{F_{cx(j-1)} \sin(\theta_j) + F_{cy(j-1)} \cos(\theta_j)\} a_j - F_{cy_j} b_j + M_{cz(j-1)} - M_{cz_j}) / I_j \quad (1)
\end{aligned}$$

where  $i=1:n_a$  and  $n_a$  is the number of axles per unit,  $j=1:n$  and  $n$  is the number of units. Parameters  $m_j$  and  $I_j$  are total mass and yaw moment of inertia of unit  $j$ , respectively. Here,  $F_{cx0}$ ,  $F_{cy0}$ ,  $M_{cz0}$ ,  $F_{cxn}$ ,  $F_{cyn}$  and  $M_{czn}$  are zero and  $[\theta_1 \theta_2 \theta_3 \dots] = [\delta_f (\varphi_1 - \varphi_2) (\varphi_2 - \varphi_3) (\varphi_3 - \varphi_4) \dots]$  where  $\delta_f$  is the front axle steering angle,  $\varphi_j$  is yaw angle of unit  $j$ . Parameter  $sc_{ji}$  is a coefficient assigned to the  $i_{th}$  axle of the  $j_{th}$  unit which is zero for unsteered axles and nonzero for steered axles.  $V_{x_j}$ ,  $V_{y_j}$  and  $\dot{\phi}_j$  are longitudinal velocity, lateral velocity and yaw velocity of unit  $j$ , respectively.  $l_{ji}$  is the distance between CoG (centre of gravity) and the centre of the  $i_{th}$  axles of the  $j_{th}$  unit.  $a_j$  is the distance between CoG and the centre of the front coupling point of the  $j_{th}$  unit while  $b_j$  is the distance between CoG and the centre of the rear coupling point of the  $j_{th}$  unit. Note that  $a_1$  and  $b_n$  are zero. The Pacejka tyre model for combined longitudinal and lateral slip is used for calculating tyre lateral and longitudinal forces,  $F_y$  and  $F_x$  given in (Pacejka H. 2012). More details regarding vehicle dynamics modelling can be found in (Kati M.S., et. al, 2013).

The driver model considered in this work is based on a Proportional, Integral and Derivative (PID) control design to follow a prescribed path by applying proper steering angle. The steering angle can be obtained using the following PID control:

$$\delta_f = K_p e_p + K_i \int e_p + K_d \frac{d}{dt} e_p \quad (2)$$

where  $e_p$  is the error signal between the reference path and a point in the vehicle; this point is either the path of the centre of front axle of the first unit in a single lane change manoeuvre or the path of the right outer corner of the first unit in a turning manoeuvre.  $K_p$ ,  $K_i$  and  $K_d$  are proportional, integral and derivative gains of the controller, respectively.

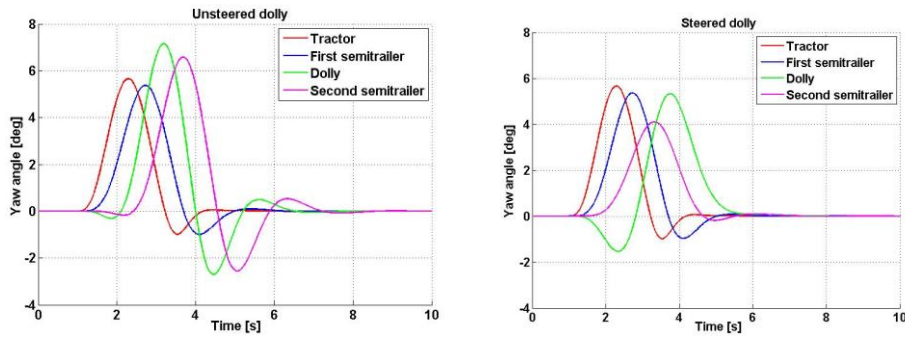
### 3. Smart dolly

Smart dolly means a dolly that can be steered, braked and propelled and can be used to enhance performance of the vehicle combination. To demonstrate the possibilities and limitations of adding steering actuation to the dolly, a proportional controller is implemented. Based on the articulation angle between the preceding unit and the dolly. Both axles of the dolly are steered with the same amount of steering according to:

$$\delta_{dolly} = K \theta_2 = K (\varphi_2 - \varphi_3) \quad (3)$$

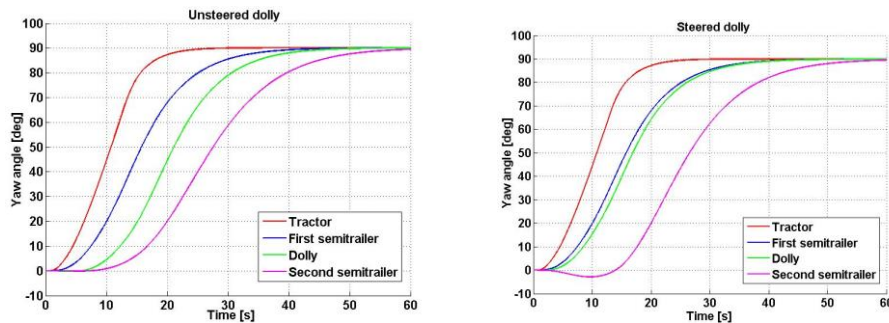
where  $K$  is a gain,  $\theta_2$  articulation angle which is difference between the yaw angles of the first semitrailer and the dolly. The  $K$  gain is manually tuned such that to achieve desired lateral PBCs such as RWA in high speed and minimum SPW in low speed. However, the control strategy is not investigated in details and is subject of future work. Through this,  $K$  becomes generally negative for low speed and positive for high speed. The control law could be interpreted as a mechanical spring, which its characteristic is to be tuned in such a way that both high speed and low speed lateral performances are improved.

Results from simulations show that in a single lane change maneuver, with a constant velocity of 80 km/h and maximum lateral acceleration of  $2 \frac{m}{s^2}$  and steer frequency equal to 0.40 Hz, the combination with the dolly steering control performs as shown in Figure 3, resulting in better lateral performance.



**Figure 3 - Yaw angles of A-double combination units in a single lane change maneuver**

At low speed 90 degree turning, the combination with the dolly steering control performs nearly the same yaw angle on the dolly as the first semitrailer, as shown in Figure 4, which will result in less low speed offtracking.



**Figure 4- Yaw angles of A-double combination units in a 90deg low speed turning**

To improve longitudinal performance characteristics of a vehicle combination, dolly axles are assumed to be driven and braked by an engine with a half of the size of the main engine on the towing unit.

#### 4. Longitudinal performance based characteristics

The longitudinal PBCs evaluation results for both combination, Tractor-semitrailer and A - double combination and also A-double equipped by propelled dolly are listed in Table 1. The propulsion added on dolly assumed to have a half of size of the main engine on the tractor which is 750hp engine.

Startability characteristics is defined as the maximum upgrade, in units of percentage, that the combination is able to start from standstill and maintain steady forward motion and be able to reach velocity of 10 km/h in 20 seconds (Kati M.S. 2013). Assuming 12% as the performance level of this characteristic, it can be seen that all three combinations can meet this level on dry road ( $\mu=0.8$ ) condition. On the wet road ( $\mu=0.6$ ), A-double cannot meet the criterion which by adding propelled dolly this can be improved. In icy condition ( $\mu=0.3$ ), all three cases fail although by adding propelled dolly to A-double, we can get the same performance level as a tractor-semitrailer. Gradeability is defined as the maximum upgrade, in units of percentage, that the combination is able to maintain steady forward motion while driving by a speed of 80 km/h without decreasing the speed (Kati M.S. 2013). As shown in the table, this characteristic is not dependent on the road grip and is engine size related where by adding propelled dolly, the performance level for A-double is improved. The performance level of acceleration

capability for assessed combinations is calculated as the time taken to accelerate from rest and travel 100 meters distance. By using propelled dolly the performance level for A-double becomes a closer value to tractor-semitrailer level in various road conditions.

**Table 1- Longitudinal PBCs assessment results at various friction road conditions**

PBCs	Startability [%]			Gradeability [%]			Acceleration capability [s]			Stopping distance [m]			Down-grade holding [%]		
	$\mu$			$\mu$			$\mu$			$\mu$			$\mu$		
Friction Coefficient	0.8	0.6	0.3	0.8	0.6	0.3	0.8	0.6	0.3	0.8	0.6	0.3	0.8	0.6	0.3
<b>Tractor-semitrailer</b>	21	15	6	4	4	4	10.8	11.5	18.2	35.7	42.8	94.2	8.7	8.7	8.7
<b>A-double</b>	15	10	3	1.9	1.9	1.9	13.2	13.8	19.9	35.8	41.9	93.4	4.9	4.9	4.9
<b>A-double (propelled dolly)</b>	22	16	6	3.5	3.5	3.5	11.4	11.9	16.8	35.8	41.9	93.4	6.7	6.7	6.7

The performance level for stopping distance for assessed combinations is calculated as the distance traveled by the vehicle to stop from an initial velocity of 80 km/h with a deceleration rate of 0.7 g which is not engine size related, therefore we cannot see changes by adding propelled dolly to the A-double. Downgrade holding capability is the maximum downgrade, in units of percentage (Kati M.S. 2013), that the combination is able to maintain steady forward motion using retarders while driving by a speed of 80 km/h which is dependent on engine braking and retarders. Therefore by adding extra propulsion to A-double we can improve the performance of A-double. As shown, this characteristics is not dependent on road grip and is power train related. As a conclusion, Using propelled dolly can improve the longitudinal PBCs such as startability, gradeability, down-grade holding and acceleration capability.

## 5. Lateral performance based characteristics

In this section, the lateral PBCs are analyzed for the tractor-semitrailer, A-double and A-double with steered dolly. The lateral assessed PBCs for the combinations are as following: Rearward Amplification (RWA) of lateral acceleration or yaw rate, High Speed Transient Offtracking (HSTO), Lateral Clearance Time (LCT), Yaw Damping Coefficient (YDC), High Speed Steady-state Offtracking (HSTO), Low Speed Swept Path (SPW), and Straight Line Offtracking (SLO) (Kati M.S. 2013).

**Table 2- Lateral PBCs assessment results**

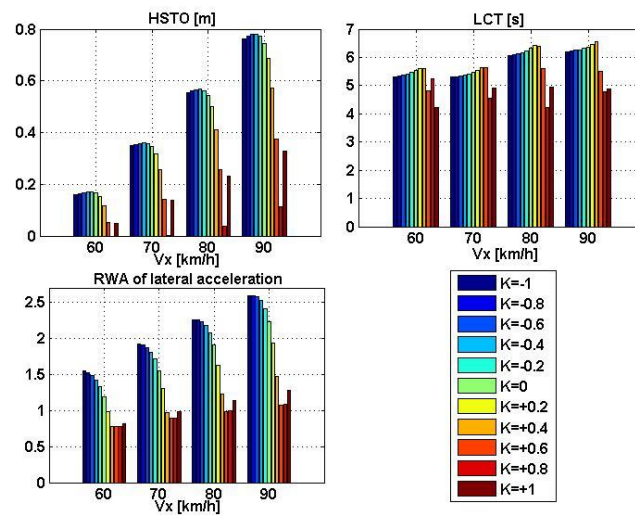
PBCs	RWA of ay [-]	SPW [m]	HSTO [m]	HSSO [m]	YDC [-]	SLO [m]	LCT [s]
<b>Tractor-semitrailer</b>	0.96	5.86	0.15	0.19	0.61	0.21	4.55
<b>A-double</b>	1.9	8.21	0.54	0.44	0.43	0.44	6.59
<b>A-double (steered dolly)</b>	0.99	7.15	0.04	0.11	0.53	0.44	4.34

Table 2 lists lateral PBCs results for the tractor-semitrailer and the A-double combination with the unsteered and steered dolly. The lateral performances considered in the next section are classified in four groups depending on the type of assessed maneuverer which are as follows (Kati M.S. 2013):

- High speed path following lane change maneuver: RWA, HSTO, LCT
- High speed sine wave steer input: YDC
- High speed turning maneuver: HSSO
- Low speed turning maneuver: SPW

### 5.1 High speed path following lane change maneuver

To assess Rearward Amplification (RWA), Lateral Clearance Time (LCT) and High Speed Transient Offtracking (HSTO) performance characteristics, a path following single lane change maneuver specified in ISO 14791 is used. The vehicle is driven with a constant velocity of 80 km/h in a single lane change maneuver that has a maximum lateral acceleration of  $2 \frac{m}{s^2}$  and a steer frequency equal to 0.40 Hz. Figures 6 shows various obtained RWA, LCT and HSTO characteristic levels for a varying range of gain K in different velocities for the frequency of 0.4 Hz. As it is shown, these characteristics have their minimum value in K larger than 0.8 which is the same for various frequencies and velocities. Therefore, to compare the effect of the steered and unsteered dolly for these characteristics the value of 0.8 and zero are chosen for gain K for the steered dolly and the unsteered dolly, respectively.



**Figure 6 - RWA, LCT and HSTO for various values of K in different velocities**

RWA is defined as the ratio of the maximum value of the motion variable of interest (e.g. yaw rate or lateral acceleration of the center of gravity) of the worst excited following vehicle unit to that of the first vehicle unit during a specified maneuver at a certain friction level and constant speed (Kati M.S. 2013). RWA of lateral acceleration and yaw rate for different units for both steered and unsteered dollies are shown in Figures 7 and 8. It can be seen that in the unsteered dolly, the dolly itself has the highest RWA of lateral acceleration which is 1.9 but in the steered dolly case the second unit has the highest RWA of lateral acceleration which is 1. Figure 9 shows the performed steering angles on the dolly and the first unit's front axle for this specific single lane change maneuver.

HSTO is defined as an overshoot in the lateral distance between the paths of the center of the front axle and the center of the most severely offtracking axle of any unit in a single lane change maneuver at a certain friction level of 0.8 and a constant longitudinal speed of 80 km/h and steering frequency of 0.4 Hz. And LCT is defined as the time taken by a combination to clear a certain lateral distance and to have the paths of the center of the front

axle and the center of all units in the same line at a certain friction level of 0.8 and a constant longitudinal speed of 80 km/h (Kati M.S. 2013).

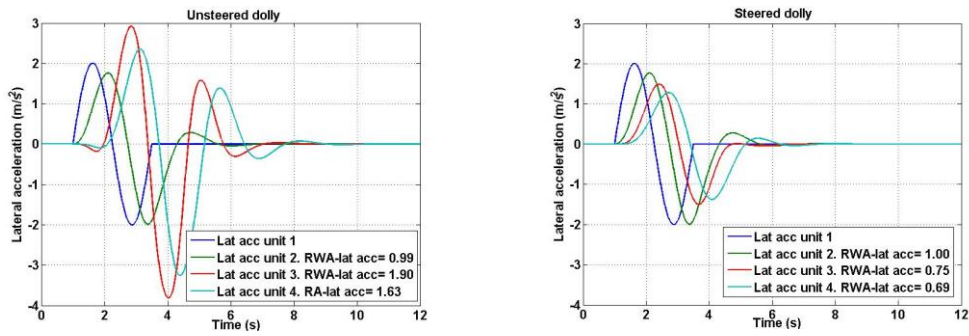


Figure 7 - RWA of lateral acceleration at velocity of 80 km/h and frequency of 0.4 Hz

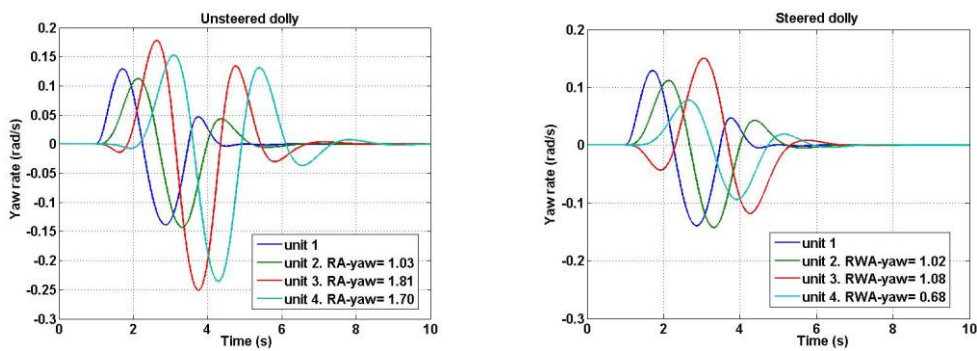


Figure 8 - RWA of yaw rate at velocity of 80 km/h and frequency of 0.4 Hz

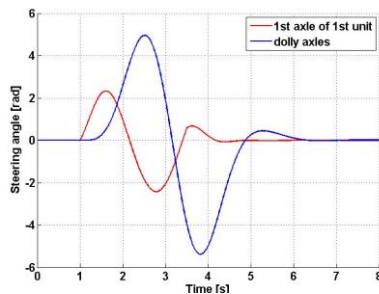


Figure 9 - Steering angles for dolly and front axle of 1st unit in defined single lane change

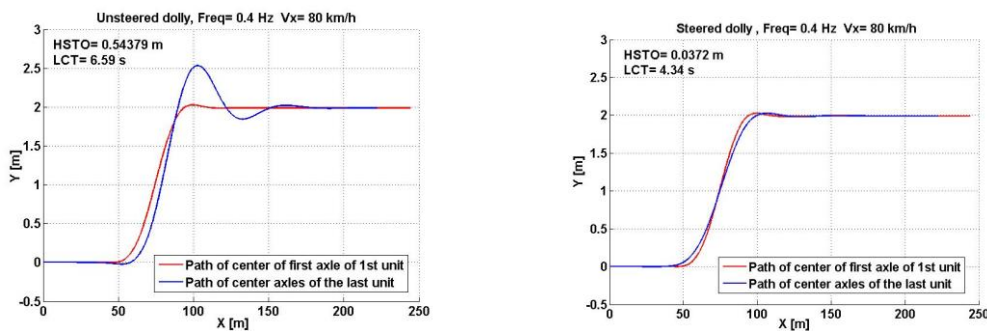


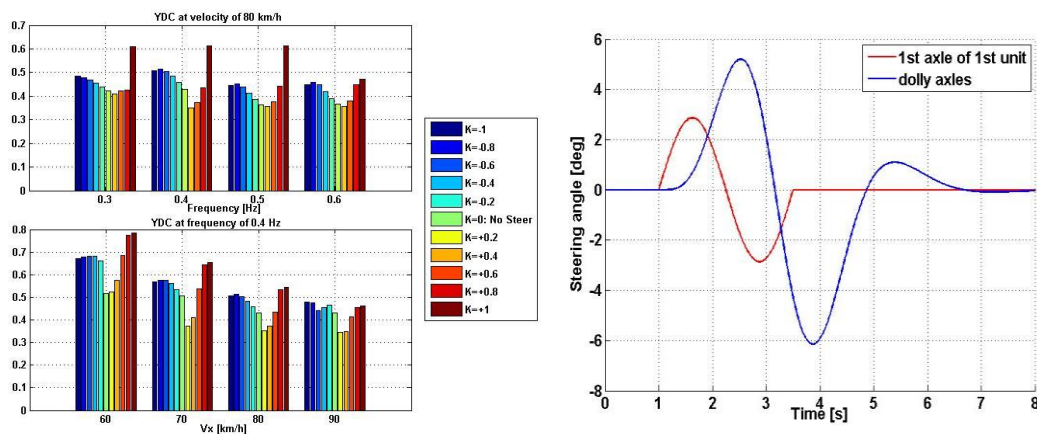
Figure 10 - Path of the first axle of the first unit and the axles of last unit

The path traveled by the first axle of the first unit and the center axle of the last unit are shown for both steered and unsteered dolly in Figure 10. As shown, the HSTO and LCT values are significantly decreased by using the steered dolly.

### 5.2 High speed sine wave steer input

Yaw Damping Coefficient (YDC) is defined as the damping ratio of the least damped articulation joint's angle of the vehicle combination during free oscillations excited by actuating the steering wheel with a certain pulse or a certain sine-wave steer input at a certain friction level (Kati M.S. 2013). YDC has been determined by applying a single sine wave steering angle with frequency of 0.4 Hz and amplitude of 0.05 rad at a velocity of 80 km/h.

The A-double combination has a proper yaw damping and as the authors stated in (Aurell J. and Wadman T. 2007), vehicle combinations which has no center-axle trailers have normally sufficient yaw damping. Considering the performance level of 0.15 for YDC according to Australian PBS (NTC 2008), the A-double combination has an acceptable YDC value is various gain K and even with an unsteered dolly case, shown in Figure 11 (left), which is much higher than 0.15 in various velocities and frequencies. Figure 11 (right) shows the steering angles performed on the front steered axle of the tractor and the dolly axles to improve YDC from 0.43 to 0.53 as listed in Table 2.

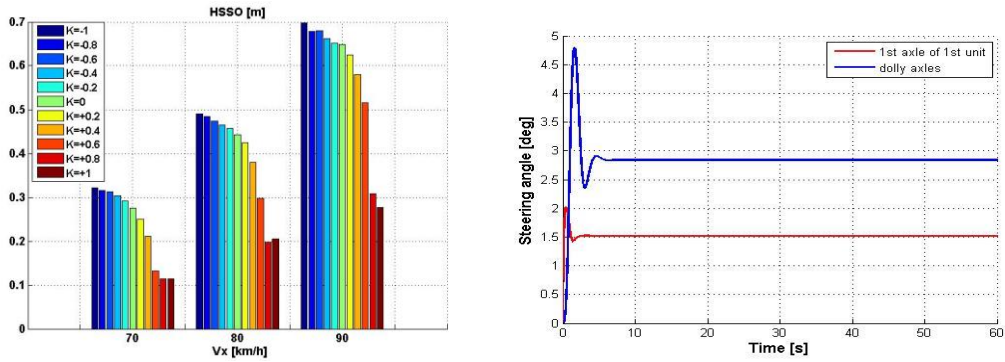


**Figure 11: (left figure) YDC level for various values of gain K in different frequencies and velocities (right figure) steering angles of front axle and the steered dolly axles for K=0.8**

### 5.3 High speed turning maneuver

High Speed Steady-state Offtracking (HSSO) is defined as the lateral offset between the paths of the center of the front axle and the center of the most severely offtracking axle of any unit in a steady turn at a certain friction level and a certain constant longitudinal speed (Kati M.S. 2013). To evaluate HSSO characteristics, a constant-radius curve of radius 319 meters negotiated at a high speed of 90 km/h with a lateral acceleration of about 0.2 g is considered. Figure 12 (left) depicts HSSO values for various values of gain K and it also shows that choosing a positive value of K gives minimum HSSO for various velocities. The required steering angles on the front axle of the tractor and the dolly axles to improve HSSO level for this specific maneuver are shown in Figure 12 (right).

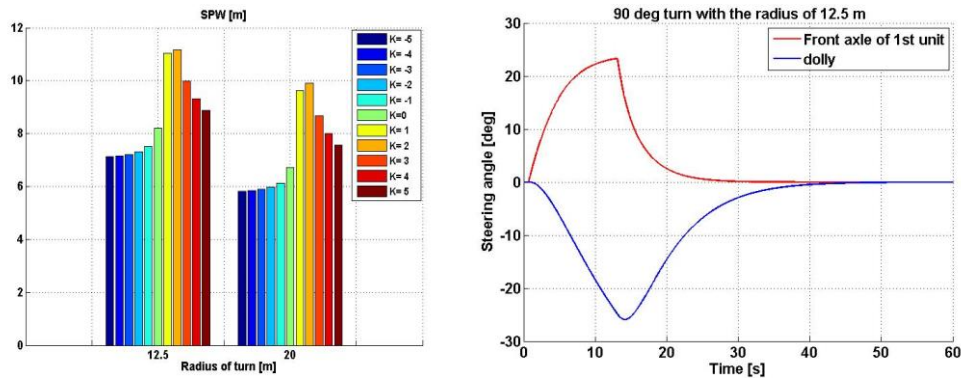




**Figure 12 - (left figure) HSSO characteristic vs gain K for various velocities (right figure) steering angles of front axle and the steered dolly axes for K=0.8**

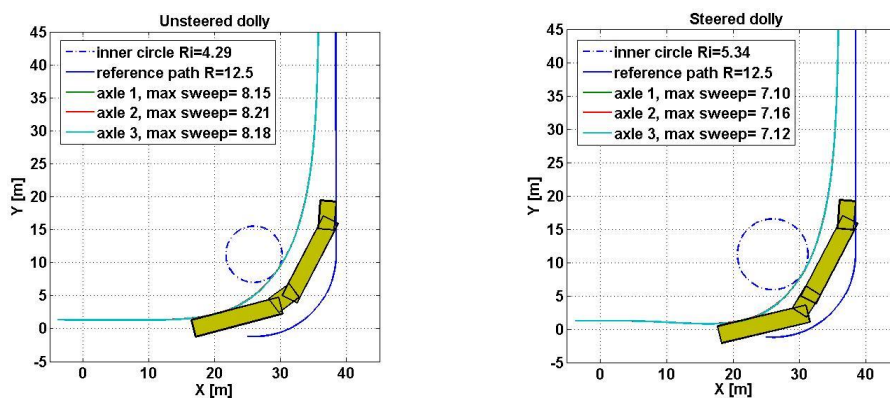
### 5.4 Low speed turning maneuver

Swept Path Width (SPW) or Low Speed Swept Path (LSSP) is defined as the maximum width of the swept path between outer most and inner most points of the vehicle combination in a low speed turn (Kati M.S., et. al, 2013).



**Figure 13: (left figure) SPW value for various K gain for 90 degree turning (right figure) steering angles of front axle of the tractor and the dolly axes**

Figure 13 (left) shows the SPW value for various gain K value for two different turning radiuses of 12.5 m and 20 m. It can be seen that for negative values of K, the SPW level is smaller for the A-double with steered dolly compared to the A-double with the passive dolly for both turning radius.



**Figure 14 - 12.5m radius and 90 degree turning maneuver**

By considering  $K=-4$ , the SPW of 8.21 m of unsteered case will be decreased to 7.16 m in the steered dolly case for a 90 degrees turning in an outer radius of 12.5 m, as shown in Figure 14 by applying the dolly steering angle shown in Figure 13 (right). The negative gain implies steering the dolly axles in the opposite direction of the steering of the front axle.

## 6. Conclusion

As discussed in the previous sections, using smart dolly will improve performance characteristics of a A-double combination and it can perform similar to an existing European tractor-semitrailer combination. For steering of the dolly in high speed, the optimum value of gain  $K$  was positive and almost similar for various high speed lateral characteristics. On the other hand, for low speed lateral characteristics, swept path width, the required  $K$  to minimize the level of this characteristics was a negative value. This indicates that for high speed stability and low speed maneuverability, the dolly needs to be steered in different direction with different amount of steering.

From a logistics company perspective there is a balance of how much fixed costs and variable costs can be added for a vehicle combination when performing typical transport missions with specific revenues. If a basic comparison is done between having two tractor-semitrailer combinations compared with having one tractor and a smart dolly with two semitrailers. In this case, the driver cost is now reduced by half, the fuel consumption is also reduced in tonne/(volume\*km). The fixed costs has reduced from one additional tractor to one smart dolly.

## 7. References

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