PERFORMANCE ANALYSIS OF AN A-DOUBLE IN ROUNDABOUTS USING NATURALISTIC DRIVING DATA

Abhijeet Behera
M.Sc. in Automotive Technology from Eindhoven University of Technology, 2020. Currently PhD student at the Swedish National Road and Transport Research Institute (VTI) and Linköping University, Sweden.

Sogol Kharrazi
PhD in machine and vehicle systems from Chalmers University of Technology, 2012. Working as senior researcher at the Swedish National Road and Transport Research Institute (VTI). Adjunct associate professor at Linköping University since 2018.

Erik Frisk
PhD in Electrical Engineering from Linköping University, 2001. Working as Professor at the Division of Vehicular System, Department of Electrical Engineering, Linköping University, Sweden.

Abstract

The focus of this paper is to use Naturalistic Driving Data to understand how the drivers manoeuvre an A-double combination in the roundabouts and evaluate performance in the roundabouts using measures like Low-Speed Swept Path (LSSP) and Tail Swing (TS). The analyses of the steering patterns and speed variations depict that the standard deviations of the responses of the drivers for a given travel direction in a roundabout are within $35°$ (17 % of the baseline) for the steering wheel angle and 8 km/h (40 % of the baseline) for the speed. It is also found that the cognitive workload of the drivers due to the steering pattern is higher in right turns compared to straight crossings through the roundabout. The performance analyses show a dependency of LSSP on the instantaneous radius obtained from the vehicle's path, and the vehicle's travel direction in the roundabout. LSSP ranges from 7.7 m for a left turn in a roundabout with an inner radius of 12 m to 3.1 m for a straight crossing in a roundabout with a 30 m inner radius. TS is observed in only one roundabout and its magnitude goes up to 0.4 m in a roundabout of 30 m inner radius.

Keywords: High-Capacity Transport, A-double, Swept Path, LSSP, Tail Swing, Performance Based Standards, Roundabouts, Driver Behaviour, Cognitive Workload

1. Introduction

The roundabout is one of the creative structural improvements in the road network that has played a vital role in enhancing traffic safety. Their compact geometries help slow down vehicles and reduce the chance of fatal accidents (Elvik, 2003). However, this compactness makes it more challenging for long heavy vehicles like High-Capacity Transport (HCT) vehicles to navigate the roundabout compared to shorter vehicles. Here, HCT vehicles refer to heavy vehicles that are longer than 25.25 m or heavier than 64 tons, which is the conventional length and weight limit in Swedish regulations. Key questions that are addressed in this paper in relation to these vehicles are how drivers manoeuvre them in the roundabouts and consequently, how these vehicles perform in the roundabouts.

Performance-Based Standards (PBS) is a regulatory scheme for HCT vehicles that includes performance measures with a quantified required level of performance (NTC, 2008). It offers these vehicles the potential to achieve higher safety and efficiency through innovative and optimized vehicle design. Low-Speed Swept Path (LSSP) and Tail Swing (TS) are two PBS measures commonly used for evaluating the performance of these vehicles in roundabouts and intersections. Hence, these measures are employed here to analyse the performance of two A-double combinations in a few roundabouts in Sweden. LSSP is the maximum width of the swept path, i.e., the maximum road width swept out by the extremities of the vehicle as it moves along the path. TS measures the maximum swing-out of the rearmost corner of the truck and/or trailers relative to the path traced by the front outer wheel of the truck/tractor in a sharp turn.

Many parameters influence LSSP. They include the roundabout's design parameters, such as radius, number of lanes, entry and exit angles, design parameters of the vehicle, like wheelbase and coupling positions, and driver's inputs, such as speed and steering angle. Simulation-based research has been used to understand the impact of these parameters on LSSP. For instance, Larsson et al. (2022) perform vehicle simulations to examine how the radius of the roundabout affects the swept path of HCT combinations for various exit angles in a roundabout. Similar research has been performed by Kharrazi et al. (2017) and Bruzelius and Kharrazi (2021). Some other prior research like (Pecchini and Giuliani, 2013), relies on test track trials and draws similar conclusions as in simulation-based studies. Contrary to LSSP, TS is briefly studied and mostly through simulations. For example, De Saxe et al. (2012) explained the influence of wheelbase on TS using 3 degrees of freedom low-speed turning model. Isted et al. (2022) performed simulations to demonstrate the variation of TS with the radius of turn. Although LSSP and TS have been studied through simulations and experiments in regulated environments, the assessment of these vehicles in roundabouts using naturalistic driving data (NDD) is missing.

NDD refers to the data source that contains measurements collected unobtrusively as the vehicle is driven in real-world traffic (Bärgman, 2016). The use of vehicle data in real traffic ensures a realistic evaluation of the behaviour of these vehicles in roundabouts. It offers an opportunity to understand the impact of infrastructure on the vehicle using real data, which has been previously evaluated through simulations. This paper assesses the impact of the design parameters of a roundabout, specifically the radius of the roundabout, on LSSP and TS. It gives an idea about the efficacy of these vehicles in different roundabouts. Moreover, the vehicle data is also used in this paper to get an insight into the driver's behaviour in roundabouts, such as their steering patterns and speed variation while navigating the roundabouts. The steering signal is further utilized to estimate the cognitive workload of the involved drivers.

The contributions of the paper are (1) Driver behaviour analysis in the roundabouts, i.e., how the drivers steer and vary the speed of an A-double combination in the roundabouts, (2) Evaluation of the cognitive workload of the drivers of this combination in the roundabouts, and (3) Estimation of the influence of the roundabout's radius on LSSP and TS using NDD.

2. Data Collection

The data collection for this study is done by Volvo Trucks. OxTS RT3000 sensor package with Differential Global Positioning System (DGPS) and Inertial Measurement Units (IMU) is used, which has a given positional accuracy of 1 cm under a clear sky (OxTS, 2020). These sensor packages are installed on the tractor and the last semi-trailer of two A-double combinations, which are driven in a naturalistic setting. One of the vehicles makes multiple trips between Gothenburg and Malmö (270 km), located in the south of Sweden whereas the other vehicle drives between the Piteå harbour and the city (20 km), located in the north of Sweden. The DGPS and IMU measurements are recorded at a frequency of 100 Hz. The measurements include positions, translational/angular velocities and accelerations of both the tractor and the last semi-trailer, and the steering wheel angle.

Figure 1 – Vehicles used for data collection.
Left: Piteå harbour-City, Right: Gothenburg-Malmö.

3. Extraction of roundabout crossings

The approach followed for extracting the roundabout crossings partially aligns with the methodology developed by Jorge (2012). The real-world positions of roundabouts are fixed, and their geographical locations can be obtained from open street maps (OpenStreetMap contributors, 2022). Since the area spanned by the vehicles' travel routes is large, it is time demanding to explore the routes manually and find out the locations of roundabouts. Hence, automatic identification of these locations is preferred. The capabilities of open street maps (OSM) are used to identify all the roundabouts in all the routes that the vehicles drive through.

With the locations of all the roundabouts known, the next step is to identify the intervals in NDD when the vehicle passes through a certain roundabout. A simple algorithm is formulated that finds the interval in which the tractor's coordinates lie within the boundaries of a roundabout. The Python codes used for identifying the roundabouts from OSM and extracting the corresponding intervals from NDD (where the vehicle has crossed the roundabouts) can be found at https://github.com/abhijeetbehera97/Roundabout-extraction.git.
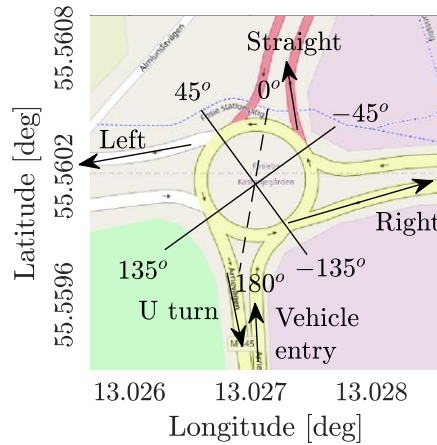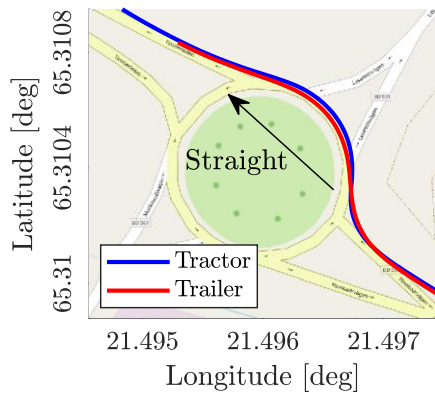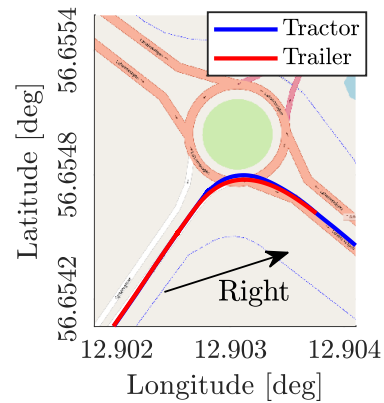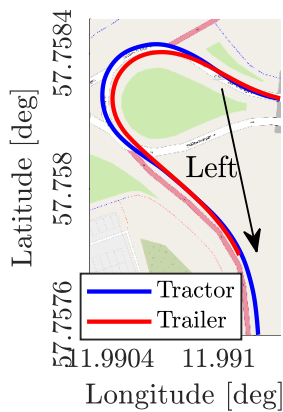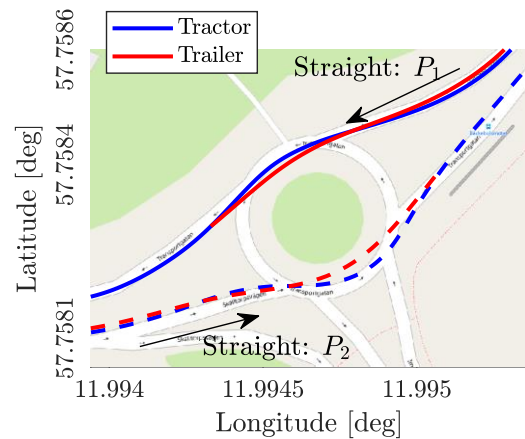
Figure 2 – Exit directions in a roundabout.

(a) R$_9$: Large Roundabout (R30)

(b) R$_6$: Medium Roundabout (R24)

(c) R$_3$: Drop-form Roundabout (R15)

(d) R$_1$: Common Swedish Roundabout (R11)

Figure 3 – Examples of extracted roundabout crossings along with the vehicle's path.

All the roundabout crossings of the considered vehicles involve four exit directions. Hence, they are categorized as: Right, Straight, Left and making a U-Turn. Note that these directions align with the driving practice (Right-hand driving) in Sweden. Figure 2 depicts a roundabout that the vehicle navigates in its travel route. An interval of angles is employed for categorizing each of the manoeuvres in a roundabout, as shown in Figure 2.

A total of 152 roundabout crossings are identified from NDD. These crossings involve 9 roundabouts, 2 of which are from the route in the north and 7 from the route in the south. Furthermore, the crossings consist of 130 instances of vehicles going straight, and 11 cases each for right and left turns. Note that there are no U-Turns made by the vehicles. Out of all cases of vehicles going straight through the roundabout, 92 are from a particular roundabout in the north; the roundabout is shown in Figure 3 (a). The remaining roundabouts fall into one of the other main types of roundabouts depicted in Figure 3. The nomenclature of the roundabouts is consistent with the description given by Larsson et al. (2022).

The roundabout's radius is obtained by fitting a circle to its inner ring. From here onwards in this paper, the inner ring's radius is denoted as the roundabout's radius for convenience. It may be noted that the inner ring is not strictly circular in all the roundabouts. Hence, the calculated radius may not be exact. Table 1 shows the list of roundabouts with their respective radius. For the sake of simplifying the analysis, roundabouts with radius values close to each other are grouped into one group. All the roundabouts have 2 lanes and the width of each lane ranges between 3 m and 4.5 m.

Table 1 – List of Roundabouts that the vehicle traverses in its route.

Case	Inner Ring Radius [m]	Outer Ring Radius [m]	Grouped Radius
R_1	11	18.5	R11
R_2	12	19.5	
R_3	15	22	R15
R_4	16	25	
R_5	16	25	
R_6	24	33	R24
R_7	24	33	
R_8	25	34	
R_9	30	38	R30

4. Driver's behaviour analysis and Cognitive workload

Figure 4 presents the variation of the steering wheel angle (δ) and speed (v) with the position (s) for the roundabouts depicted in Figure 3. The solid line (baseline) represents one crossing of a roundabout. A '0' in the abscissa represents the position where the tractor enters the roundabout's ring for this case. The shaded area represents the deviations of the remaining cases with respect to the baseline. The standard deviation of the steering wheel angle is the largest in the ring area. It ranges from 5° (~ 2 % of the baseline) in Figure 4 (f) to 35° (~ 17 % of the baseline) in Figure 4 (c). With respect to the speed, the standard deviation is the largest in the region before entering the ring. It varies from 3 km/h (~15 % of the baseline) in Figure 4 (d) to 8 km/h (~ 40 % of the baseline) in Figure 4 (a). Although there is a substantial variation in the standard deviation of the driver responses, the response patterns are similar for a given travel direction in a roundabout.

It is evident from some of the roundabouts, for example, R_9 and R_1, that the drivers perform a series of manoeuvres to traverse the roundabout. It involves counter-steering, steering, and counter-steering in succession. The counter-steering manoeuvres create space for the trailing units of the vehicle while entering and exiting the ring.
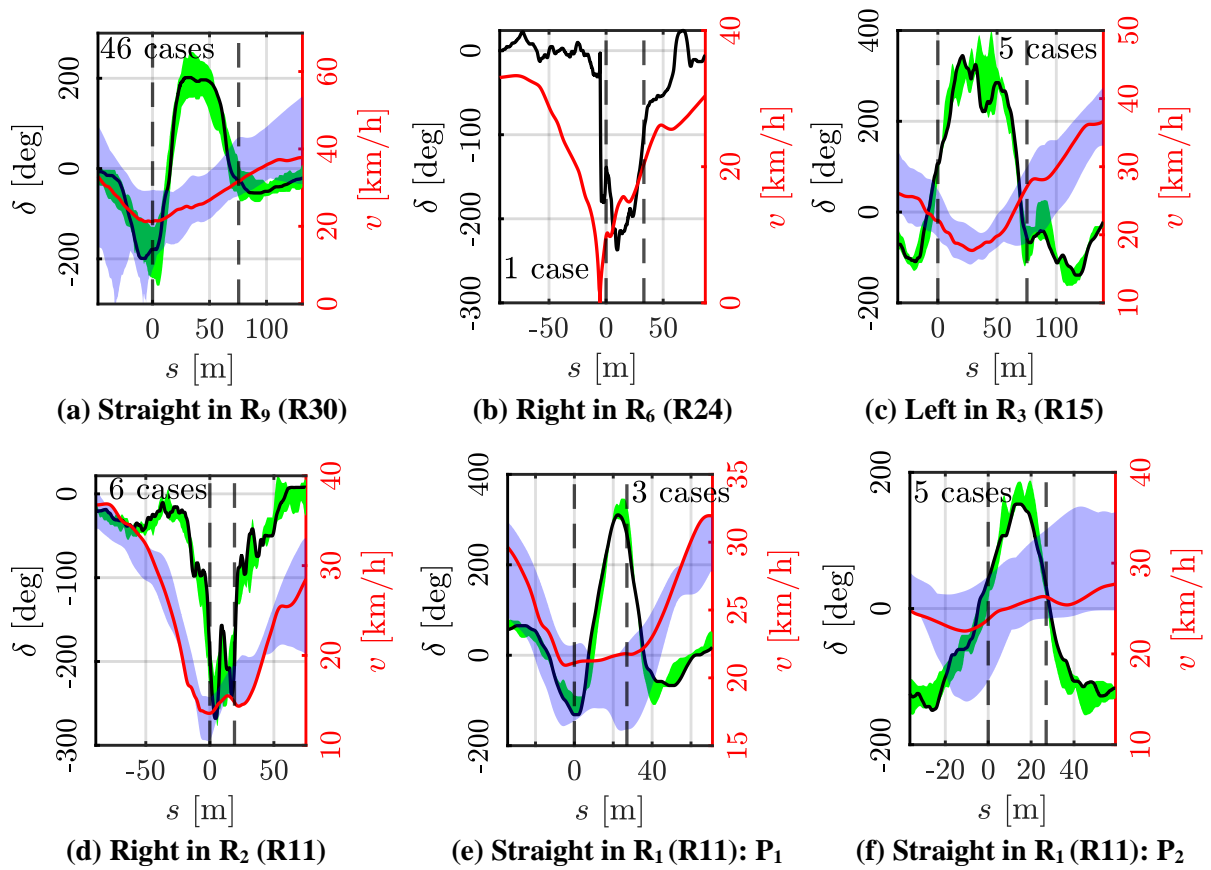
Figure 4 – Driver inputs. Dashed lines show the ring intervals. Black and red solid lines indicate the baseline for steering wheel angle and speed respectively. The deviations from the baseline for steering wheel angle and speed are shown by the shaded area in green and purple respectively. P_1 and P_2 in (e) and (f) denote crossings in opposite directions as shown in Figure 3 (d).

It can be observed from the figures that the speed of the vehicle decreases as it enters the ring. The decrease can be attributed to the entry angle of the roundabout and the traffic in the ring (Kennedy et al., 2007). Thereafter, the speed increases as the vehicle travels through the ring. The increase may be attributed to two factors. First, a higher radius of curvature at the roundabout's exit and ring, compared to the entry, and second, the vehicles inside the roundabout have the right-of-way over the drivers entering the roundabout.

Figure 5 (a) shows box plots of the entry and exit speeds in the roundabout crossings. The entry and exit speeds are the speed of the tractor when entering the ring and the speed of the trailer when exiting the ring. On a closer look at each of the box plots, it can be observed that the median of exit speed is more than twice the median of the entry speed. It means that irrespective of the travel direction, type and radius of the roundabout, the vehicle speeds up approximately by a factor of 2 or more as it traverses through the roundabout. Furthermore, the medians for both the entry and exit speed cases increase with the radius of the roundabout. This is expected as with an increase in radius, the path becomes less curvy, and consequently, the entry and exit speeds of the vehicle increase. A slightly high median for the 11 m roundabout (R11) is obtained due to a less curvy path P_1, which allows the vehicle to exit the ring at a high speed.

Drivers use a combination of speed and steering inputs to navigate in a roundabout, which results in an increased cognitive workload for the drivers in the roundabout compared to usual straight-line driving. Steering Reversal Rate (SRR) is employed to measure the workload in the roundabouts. SRR represents the number of times per minute that the steering-wheel direction is reversed by a minor adjustment greater than a specified threshold. To calculate SRR, the approach described by Markkula and Engström (2006) is employed. A low-pass Butterworth filter with a cut-off frequency of 1 Hz and a threshold of 3 degrees is used to eliminate the effect of normal angular variability in the steering wheel signal caused by noise. The threshold is considered from a previous study by Pecchini et al. (2017), which estimated SRR for a heavy vehicle in a roundabout.
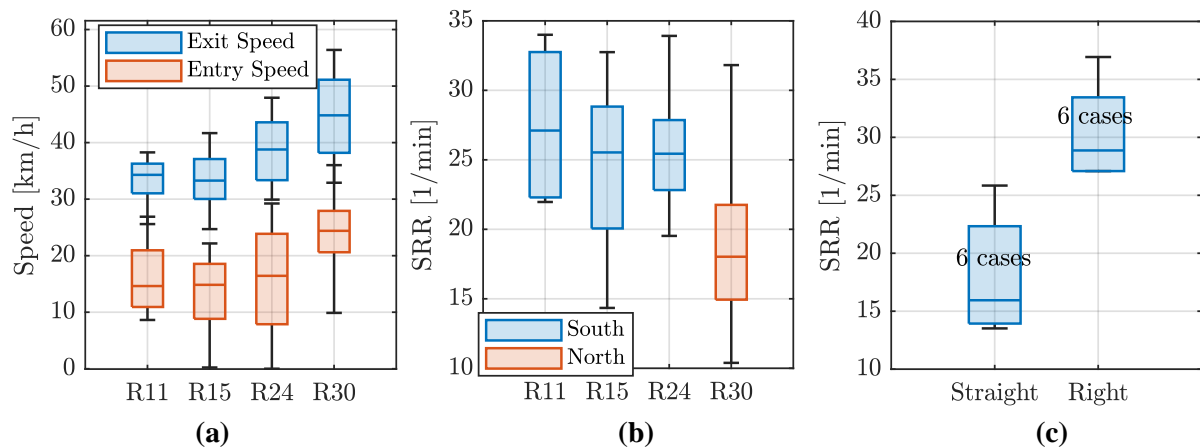
Figure 5 – (a) Entry and exit speeds obtained in the roundabouts. (b) SRR in different roundabouts for straight crossings. (c) SRR for two different travel directions in R$_2$ (R11).

Figure 5 (b) displays the SRR with roundabouts involving straight crossings. The roundabout in the north has the lowest median amongst all others, indicating the least workload on drivers. There could be two reasons for this observation. Firstly, the roundabout in the north has a high radius, resulting in a less curvy path for vehicles and making it easier for drivers to navigate. Secondly, the traffic density is lower in the north compared to the south, resulting in a smaller number of adjustments needed for the vehicle to manoeuvre in the roundabout. The traffic density can also be a reason why the medians of SRR in the south are only mildly decreasing despite a considerable increase in the radius of the roundabout.

Figure 5 (c) represents the SRR for two travel directions in the roundabout R$_2$. The median associated with the right turn is more than the straight crossings, indicating a higher workload with right turns. This observation is concurrent with the previous study by Pecchini et al. (2017) on a heavy vehicle. It concluded that a right turn is more workload intensive than a straight crossing in a roundabout.

5. Performance analysis

This section is divided into two parts. The first part deals with analysis using the swept path and the second part involves tail swing analysis.

a. Swept Path Analysis

The trajectories of the vehicle are different for different travel directions. It results in the vehicle occupying a different amount of space (swept width) at different locations of the roundabout. Figure 6 (a) shows the variation of the swept width with the position along the roundabout for a sample case for each travel direction. The corresponding vehicle paths are displayed in Figure 6 (b). A '0' in the abscissa represents the location where the trailer enters the ring.
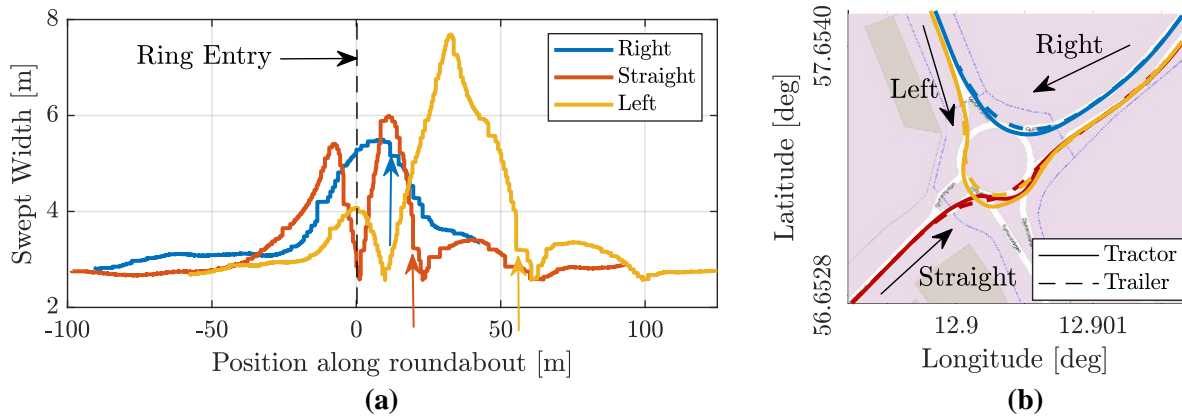
Figure 6 – Swept width for different travel directions in R$_2$ (R11). Upward arrows in (a) are at the locations where the vehicle exits the ring for a given travel direction.

Three peaks in the swept width are observed when the vehicle is going straight or turning left in the roundabout. The magnitude of the peak is highest at the ring, followed by the peaks obtained while entering and exiting the roundabout. The difference in the magnitude of the peaks is substantial for the cases where the vehicle is turning left compared to going straight in the roundabout.

The entry angle of a roundabout can have a significant influence on the swept path of the vehicle. Among all the analysed roundabouts in this study, the roundabout R$_9$ (radius of 30 m) has the highest entry angle. Hence, R$_9$ is chosen for further analysis. The peaks (maximum swept width) from the entry, ring and exit regions are collected for all the crossings in R$_9$ and displayed in Figure 7. In 47 out of 92 cases, the peak at the entry is more than that of the ring. This is due to a considerably large counter-steering required to negotiate the high entry angle of the roundabout, see Figure 4 (a). Since such an entry angle is not present in the other roundabouts, the swept width's peak at the entry is less than the peak at the ring for them.
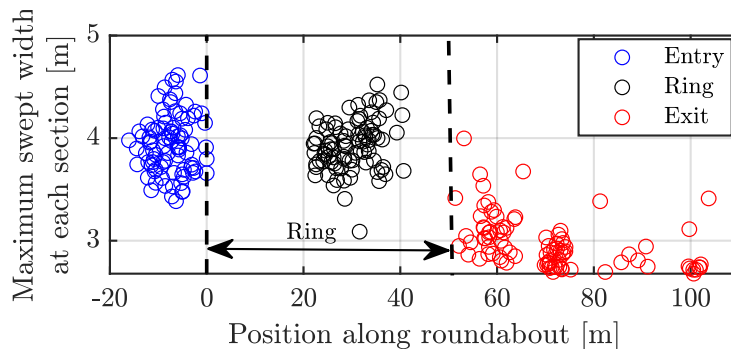
Figure 7 – Maximum swept width at entry, exit and ring in R$_9$ (R30).

Figure 8 shows the variation of the Low-Speed Swept Path (LSSP) with the instantaneous radius for the radii mentioned in Table 1. LSSP, as introduced earlier, is the maximum width of the swept path. All the displayed quantities are calculated when the vehicle is at the ring. This allows a fair comparison with the previous research where the LSSP is calculated at the ring. The instantaneous radius is the radius of the path traced by the tractor's outer wheel averaged over 0.5 m around the position where the maximum of the swept width is obtained.

(a) Straight   **(b) Left**   **(c) Right**
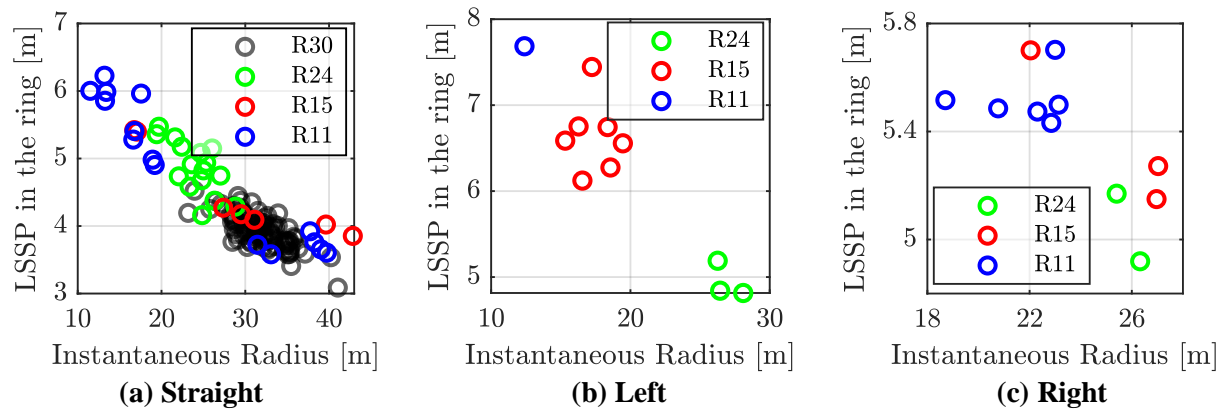
**Figure 8 – LSSP in the ring for different travel directions in different roundabouts.**

It is observed from Figure 8 (a) that LSSP, irrespective of the radius of the roundabout, decreases with the increase in instantaneous radius. The reason can be attributed to the path of the vehicle that becomes less curvy with the increase in the instantaneous radius. Consequently, it decreases the swept path of the vehicle. With a lower radius roundabout, the vehicle's path in the ring can be concentric or eccentric to the inner ring. Hence, the instantaneous radius obtained in such roundabouts varies substantially, for example, look at 15 m radius (R15) cases in Figure 8 (a). Note that the large variance seen in the LSSP of the 11 m radius roundabout (R11) can be due to the different curvature of paths traversed by the vehicle, see Figure 4 (e) and Figure 4 (f). One path (P_2) is curvier than the other (P_1). With an increase in the radius of the roundabout, for instance, with the 30 m radius cases (R30), the vehicle's path becomes more concentric. The instantaneous radius increases and the variance in it decreases.

Figure 8 (b) shows the variation for all the cases where the vehicle turns left in the roundabout. LSSP decreases with the increase in both the instantaneous radius and the roundabout's radius. It may be noted that the vehicle's path must become concentric with the inner ring to undertake a left turn in a roundabout. Hence, the instantaneous radius in all the cases is within two lane widths of the roundabout's radius. Figure 8 (c) depicts the variation for the cases where the vehicle turns right in the roundabout. There is not any notable trend observed with LSSP and instantaneous radius.

b. Tail Swing Analysis

Tail Swing (TS) is mostly observed with sharp turns like in a conventional intersection. The roundabout facilitates a smooth turn for the vehicle. Hence, TS is insignificant with almost all the roundabouts except one, R_9. This roundabout has rather a high entry angle that forces the vehicle to make a sharp manoeuvre at the entry of the roundabout. This introduces a swing out of the rearmost corner of the trailer. Figure 9 displays the variation of the tail swing with the instantaneous radius at the entry. Although an inverse relationship is expected between the

quantities (Isted et al. 2022), it is difficult to conclude such a trend from the data. The reason can be inaccuracy in the sensors, specifically for the cases where the magnitude of TS reaches the accuracy limits of the sensors.
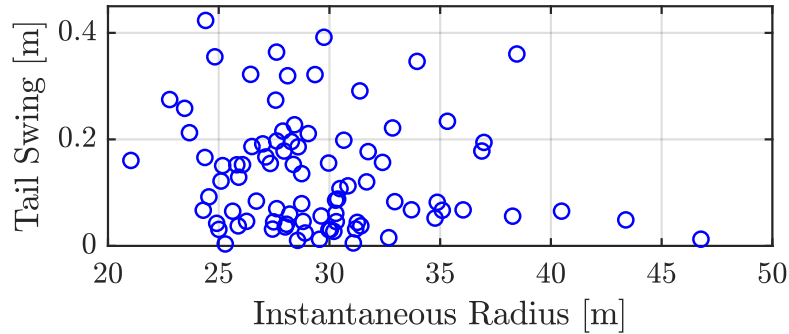
Figure 9 – Tail Swing in R_9 (R30).

6. Comparison with previous research

Figure 10 compares the results presented in this paper with previous research by Larsson et al. (2022), where simulations on an A-double, with approximately the same dimensions as vehicles considered for this paper, are performed. Manoeuvres are simulated in roundabouts which are considered rings, with exit angles of 90°, 120° and 180°. The angles, 90° and 120°, correspond to left turns in this paper, see Figure 2. Hence, all the left turns are considered for comparison with the LSSP, and the instantaneous radius obtained from the ring. A coherence is observed between the results presented in this paper and the previous research. This indicates that the simulations are representative of the results obtained in this research.
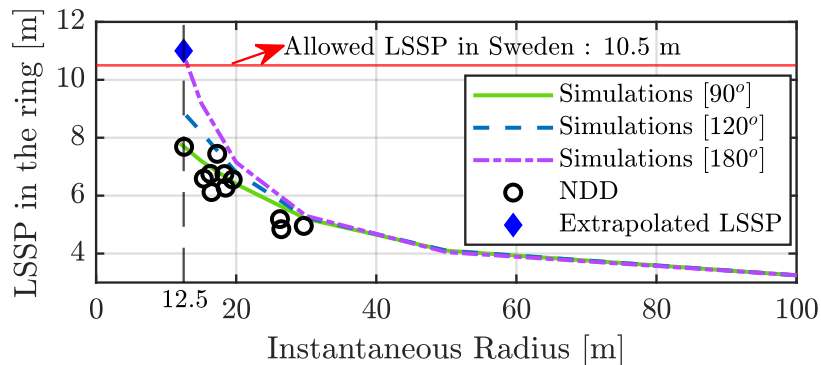
Figure 10 – Comparison with Larsson et al. (2022) for left turns. The red line shows the required LSSP for 25.25 m vehicle combinations in Sweden, in a roundabout with an outer radius of 12.5 m.

Table 3 gives an overview of the LSSP and TS obtained from this research with the standards in Sweden and other countries. The maximum LSSP achieved in this research is 7.7 m, with an instantaneous radius of 12.5 m for a left turn. By extrapolating this value using simulations (see Figure 10), an LSSP of 11.2 m is obtained for a 180° turn in an outer radius of 12.5 m, which is larger than the allowable LSSP of 10.5 m for 25.25 m vehicle combinations in Sweden. As a result, extra steerable axles would be required for these vehicles to conform to the existing LSSP requirements.

Table 3 – Overview of the PBS values from different countries (Kharrazi et al., 2013)

PBS Measures	Australia[1]	New Zealand	Canada[2]	Sweden	NDD
LSSP [m]	7.4, 8.7, 10.6, 13.7 (90º turn of 12.5 m outer radius)	7.6 (120º turn of 12.5 m outer radius)	8.5 (90º turn of 11 m outer radius)	10.5 (180º turn of 12.5 m outer radius)	7.7 (Left turn with an outer radius of 12.5 m in R_2)
TS [m]	0.3, 0.35, 0.35, 0.5 (90º turn of 12.5 m outer radius)	0.3 (90º turn of 12.5 m outer radius)	Not regulated in Canada	Not regulated in Sweden[3]	0.4 (Straight with an outer radius of 24.5 m in R_9)

[1]   Different values for LSSP and TS in Australia correspond to different access levels.
[2]   Offtracking is considered in Canada instead of LSSP. A trackwidth of 2.5 m is assumed to obtain LSSP.
[3]   Not regulated in Sweden (Kharrazi and Karlsson 2015). However, an EU directive exists which suggests a maximum tail swing of 0.8 m for single-unit vehicles in a roundabout with an outer radius of 12.5 m (ECE 1997).

7. Conclusions

The performance of A-double is assessed in 9 roundabouts with the inner radius varying from 11 m to 30 m. The following conclusions are made from the analyses of the data:
   a.   While navigating a roundabout, the standard deviation of the steering wheel angle is the largest in the ring area.
   b.   The vehicle speed increases with the radius of the roundabout. Speed is mostly higher at the exit than at the entry of the roundabout, see Figure 5 (a).
   c.   The right turns are more workload intensive than straight crossings, see Figure 5 (c).
   d.   The entry angle of a roundabout can have a significant influence on the swept width, see Figure 7.
   e.   Irrespective of the roundabout's radius, the LSSP of the vehicle decreases with the instantaneous radius for the straight and left turns, see Figure 8 (a) and Figure 8 (b).
   f.   The path of the vehicle is more concentric in a left turn compared to going straight. Hence, the instantaneous radius for the left turn varies less than that of going straight for a given roundabout, see Figure 8 (a) and Figure 8 (b).
   g.   The TS is observed in only one roundabout with a high entry angle. No conclusions can be drawn about the trend due to their magnitudes reaching the sensor's accuracy limits.
   h.   The considered vehicle will need extra steerable axles to satisfy the existing LSSP requirement for 25.25 m vehicle combinations in Sweden.

8. Acknowledgements

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