INFLUENCE OF TIRE-ROAD FRICTION ON THE PERFORMANCE OF AN A-DOUBLE IN ROUNDABOUTS AND INTERSECTIONS



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Abstract

This paper investigates the influence of tire-road friction on the performance of a long combination vehicle, specifically the A-double, during low-speed manoeuvres such as navigating roundabouts and intersections. Using real-world naturalistic driving data and applying the Performance-Based Standards scheme, the study assesses the low-speed swept path (LSSP) and the driver's response to varying friction conditions. Results indicate that tire-road friction has minimal effect on the LSSP, which conforms with earlier simulation-based studies. However, it influences driver behaviour, particularly in roundabouts where speed reductions are observed under low-friction conditions.

Keywords: Long combination vehicles, A-double, Performance-Based Standards, Low-speed swept path, Friction, Roundabout, Intersection

1. Introduction

In December 2023, the Swedish government introduced two long combination vehicles (LCVs), A-double and AB-double, on the selected road network across Sweden. In Sweden, an LCV is a heavy vehicle composed of multiple units connected in a series with a total length exceeding 25.25 m. Before this decision, a few LCVs had been granted exemptions on specific roads for trials in the last decade. These trials facilitated the collection of naturalistic driving data (NDD) in real-world traffic conditions. Previous research on this data, such as Behera et al. (2024), has analysed the performance of two LCVs (A-double and DuoCAT) in different scenarios such as lane changing, manoeuvring through roundabouts, turning at intersections, and negotiating curves. The research offered a realistic assessment of the performance, specifically the stability and tracking abilities of the evaluated LCVs in various scenarios. It was observed that weather factors like temperature and rainfall influenced the performance of vehicles, likely due to their effect on tire-road friction. However, due to project constraints, tire-road friction was not directly measured. Hence, its impact on the vehicle's performance could not be investigated. This paper aims to fill part of that gap by analysing the influence of tire-road friction on the performance of an A-double during low-speed manoeuvres like navigating roundabouts and intersections. Hence, the objectives of this paper are:

- Evaluate the effect of tire-road friction on the low-speed swept path (LSSP), a Performance-Based Standards (NTC, 2008) measure that quantifies the maximum road width swept out by the vehicle's extremities as it moves along the path.
- Investigate how tire-road friction influences the driver's speed selection, considering potential adaptations made in response to varying friction conditions.

The literature on tire-road friction in the context of heavy vehicles, specifically articulated vehicles, has predominantly focused on two key research areas. The first group aims to develop innovative methodologies for real-time friction estimation. For example, see Gao et al. (2023), and Sharifzadeh et al. (2023). The second revolves around using tire-road friction to design motion planning and control algorithms. For example, see Karimyan et al. (2024) and Li et al. (2024). Most of these studies, however, concentrate on single-unit or single-articulated heavy vehicles. The unique dynamics of LCVs due to their extended length and multiple articulation points present distinct challenges that have not been fully explored in the context of tire-road friction. Kharrazi et al. (2017) performed full vehicle simulations to understand the impact of friction in lane changes and roundabouts. Studies such as Bruzelius et al. (2021) and Larsson et al. (2022) have also explored this research direction using full vehicle simulations in roundabouts. However, an assessment with real-world data is still missing and is the focus of this paper.

The performance of an LCV is also influenced by how it is being driven in different friction conditions. Previous studies on cars such as Maia et al. (2021) have observed that driver adjusts their speed, i.e. decrease the decelerating rate to avoid any loss of control. Chen et al. (2020) have performed simulations with LCVs and showed with a driver model that the distance required to evade an obstacle increases with an increase in the speed in low-friction compared to high-friction. However, the real-world driver response remains largely unexplored for LCVs in the existing literature and is covered in this paper.

By addressing these research gaps, this study provides an understanding of how tire-road friction affects both the LSSP and the speed selected by the driver of an A-double. The A-double considered in this paper consists of a tractor followed by a semitrailer and a full trailer.

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 trailer of the A-double combination shown in Figure 1 (a), which is driven in a naturalistic setting. The vehicle makes multiple trips between the Piteå harbour and the city (20 km), located in the north of Sweden, see Figure 1 (b). The dimensions, axle load and tire specifications of the A-double are given in Appendix. 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 trailer.

(a) A-double **(b) Route**

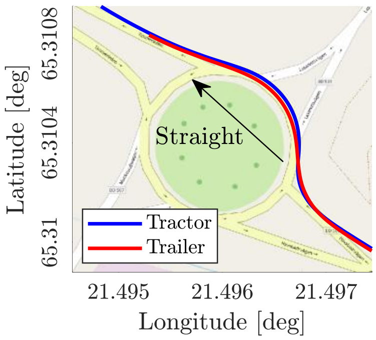
Figure 1 – A-double vehicle used for data collection along with the route followed.

Friction estimation is conducted by researchers at Luleå University using the method described in Casselgren et al. (2012). The process begins with road condition classification based on changes in reflectance from three laser diodes. These changes occur due to variations in light absorption and scattering caused by different road surfaces. Once the road condition is classified, friction is estimated accordingly. In this study, the estimated friction is synchronized with OxTS data using GPS timestamps.

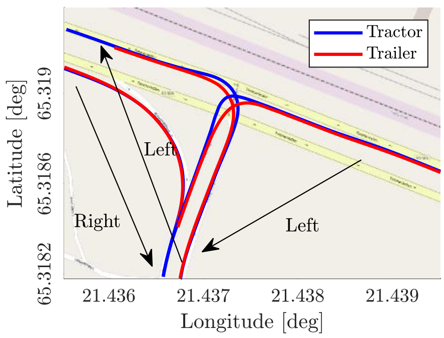
3. Extraction of roundabout and intersection crossings

The approach employed for extracting the roundabout and intersection crossings has been adopted from Behera et al. (2024). 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-consuming to explore the routes manually and find the locations of roundabouts and intersections. Hence, automatic identification of these locations is preferred. The capabilities of open street maps (OSM) are used to identify all the roundabouts and intersections in all the routes that the vehicles drive through. Figure 3 illustrates the only roundabout, and the two intersections identified within the area where the A-double is being operated and some examples of paths the vehicle follows.

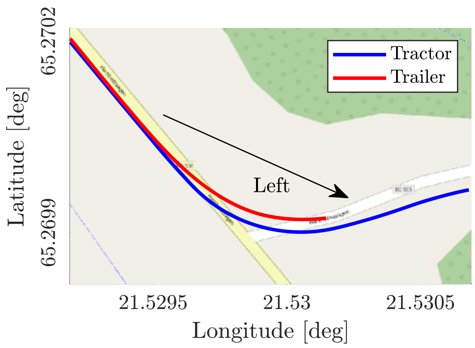
With the locations of the roundabouts and intersections known, the next step is to identify the intervals in NDD when the vehicle passes through a certain roundabout. A simple algorithm is formulated that finds the interval in which the tractor's coordinates lie within the boundaries of a roundabout and an intersection. A total of 147 straight crossings are obtained with the roundabout R_1. At intersection I_1, there are 111 left turns and 98 right turns, while intersection I_2 has 109 left turns and 113 right turns. It may be noted that the A-double makes only straight crossings in the roundabout whereas both left and right turns are performed in the intersections.



(a) Roundabout R_1 (R30): Straight



(b) Intersection I_1: Left and Right turns



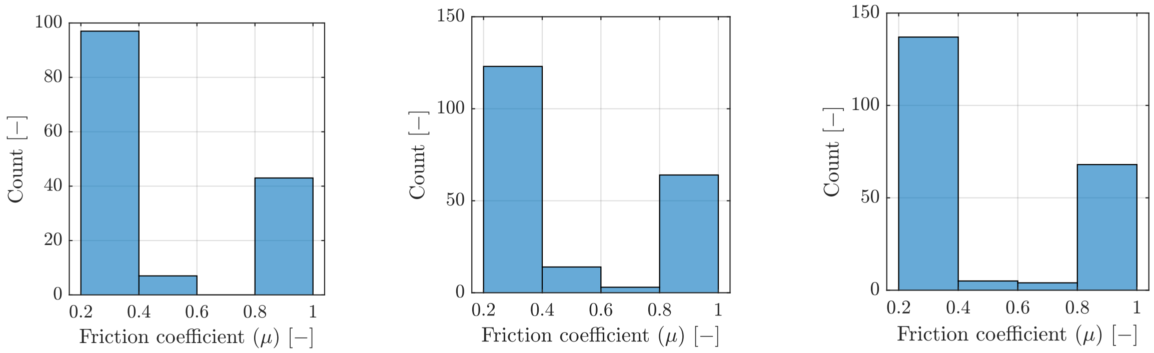
(c) Intersection I_2: Right turn

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

4. Tire-road friction coefficient

An estimate of the tire-road friction coefficient (μ) is obtained at each time step, synchronised with OxTS. The friction coefficient is relatively the same for a given location such as a roundabout or intersection. Here, the friction coefficient is averaged over the ring section of the roundabout and within a 35-meter span on either side of the intersection.

Figure 4 shows the distribution of friction coefficient found across all roundabout and intersection crossings. It is clear from the figures that there are a significant number of crossings with friction coefficients less than 0.4 and more than 0.8 for both the roundabout and intersections. The former range corresponds to low-friction conditions whereas the latter can be regarded as high-friction.

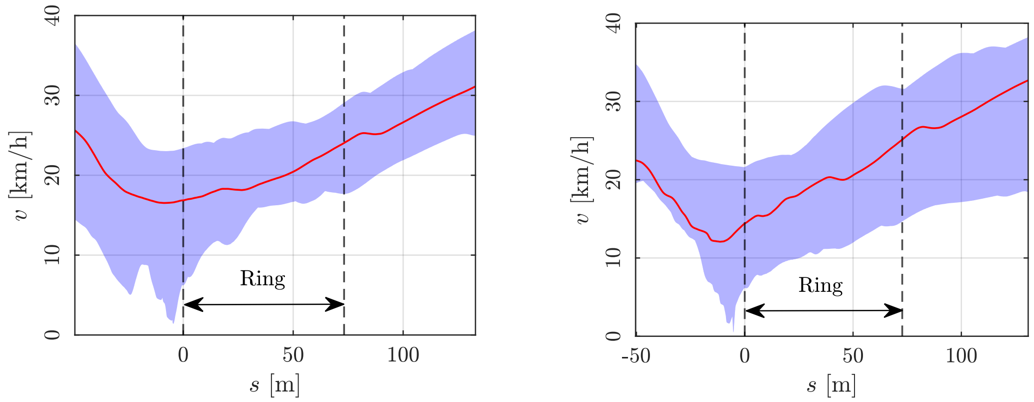


(a) (b) (c)

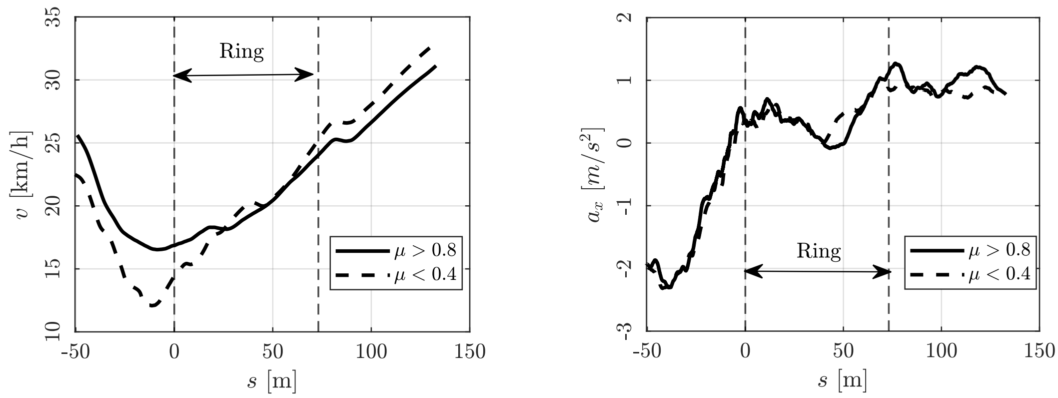
Figure 4 – (a) Roundabout R_1 (b) Intersection I_1 (c) Intersection I_2

5. Driver response to low and high friction conditions

In a roundabout, the driver slows down the vehicle to give way to the existing traffic as it is about to enter the ring of the roundabout. Subsequently, it speeds up as it navigates through the ring and exits the roundabout. Figure 5 shows the driver response for low and high friction conditions in the roundabout R_1.



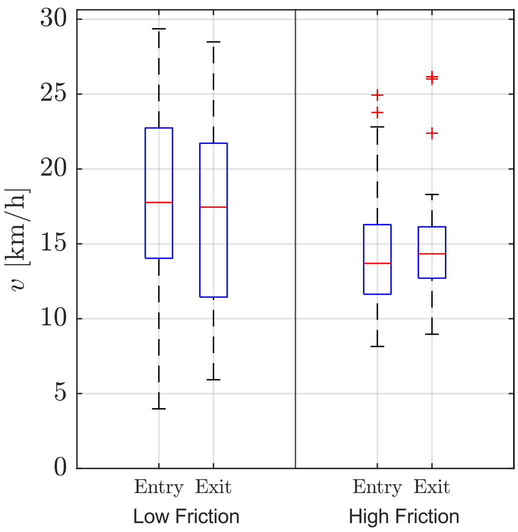
(a) Speed variation at high friction **(b) Speed variation at low friction**



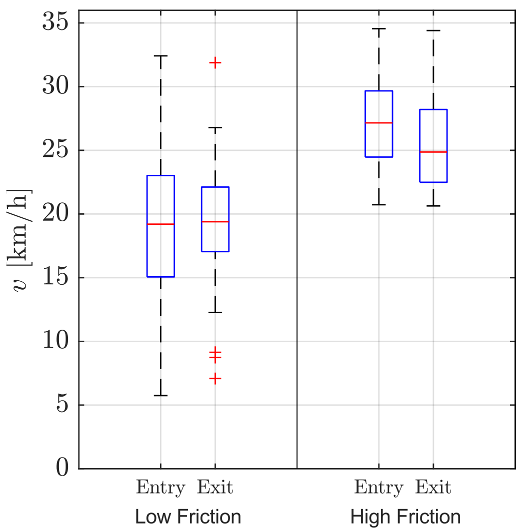
(c) Comparison of mean speed **(d) Comparison of mean longitudinal acceleration**

Figure 5 – Driver response at roundabout R_1 for high and low friction conditions. Red line in the top plots shows the crossing closest to the mean and shaded area shows the deviation.

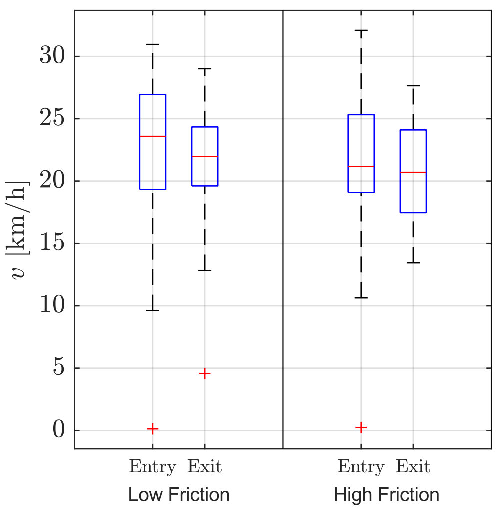
Figure 5 (a) and Figure 5 (b) show the variation of speed (v) with the position (s) for the roundabout. The red solid line belongs to a crossing which is the closest to the mean of the speed curves at each position (s). '0' in abscissa indicates the position where the tractor enters the roundabout's ring for this case. The shaded area represents the deviations of the remaining cases with respect to the solid line. There is a substantial deviation in the driver responses in both friction conditions, with the deviation in low-friction being relatively larger than the high-friction. The response patterns are similar for both conditions, i.e. the driver first decelerates and then accelerates as it enters the ring of the roundabout. A closer observation of the mean speed (Figure 5 (c)) reveals that the entry speed into the roundabout is lower under low-friction conditions. Lower speed ensures better controllability of the vehicle even though the retardation rate is the same as the high friction, see Figure 5 (d).



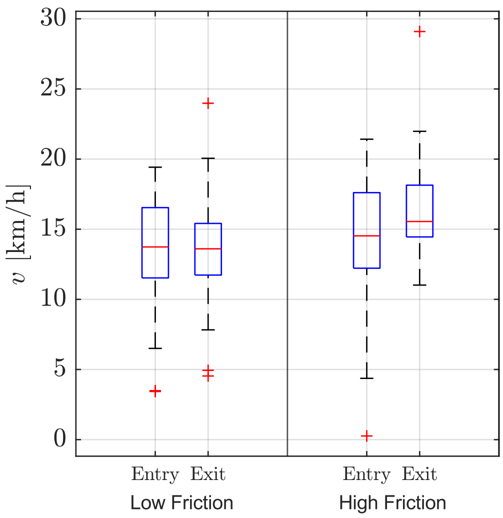
(a) I_1: Left turns



(b) I_1: Right turns



(c) I_2: Left turns



(d) I_2: Right turns

Figure 6 – Entry and exit speeds at Intersections I_1 and I_2 for low and high friction conditions in left and right turns (+ are the outliers).

The intersections shown in Figure 3 involve sharp turns and entering a freeway, leading to low speeds. Figure 6 (a) and Figure 6 (b) depict the mean speed for all the left and right turns associated with Intersection I_1 for low and high friction conditions. There is a disparity in the entry and exit speeds for low-friction and high-friction conditions for both left and right turns. Generally, the driver is expected to slow down the vehicle to cope with low-friction conditions. While the expected behaviour is observed in right turns, an opposite behaviour is observed in left turns. The left turn at Intersection I_2 involved an uphill at the exit with a large radius. Consequently, the driver increased the vehicle's entry speed to negotiate the curve. The difference in the speed level for Intersection I_2 between high and low-friction conditions is small compared to Intersection I_1, see Figure 6 (c) and Figure 6 (d). While the difference is in the intuitive direction for the right turns, it is the opposite for the left turns. Similar to I_1, the surrounding traffic may have an impact on the response of the driver.

6. Performance analysis

Figure 7 shows the variation of the Low-Speed Swept Path (LSSP) with the instantaneous radius for straight crossings in roundabout R_1 at both low and high friction conditions. LSSP, as introduced earlier, is the maximum width of the swept path. 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.

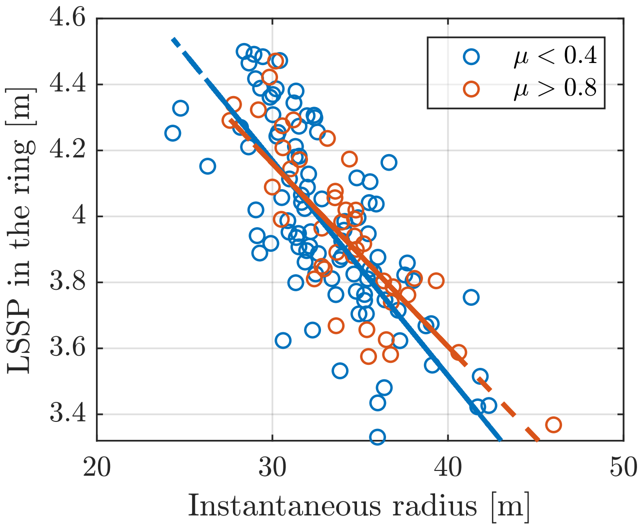
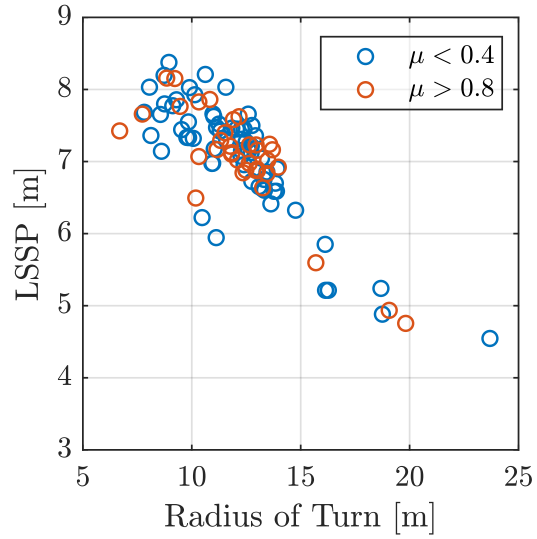


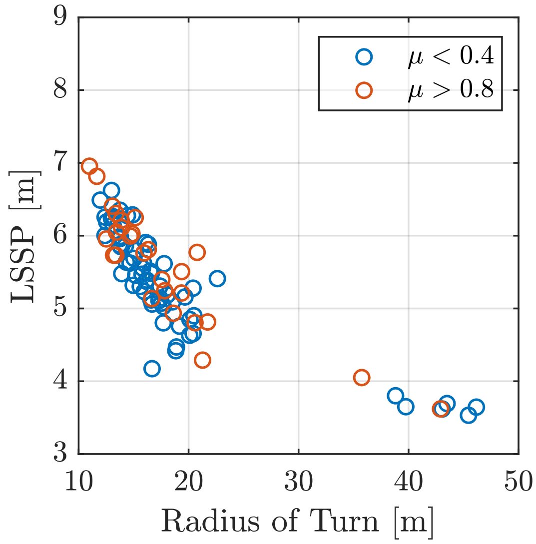
Figure 7 – LSSP in the ring for straight crossings in roundabout R_1. The dashed line is a line fitted to the data.

Similar to the trend observed in the previous studies (see Behera et al. (2024)), the LSSP decreases with the instantaneous radius. The decrease in LSSP can be attributed to the straightening of the path as the instantaneous radius increases. Moreover, there is no significant difference in LSSP between friction levels for a given instantaneous radius as can be seen with the data points and the fitted line.

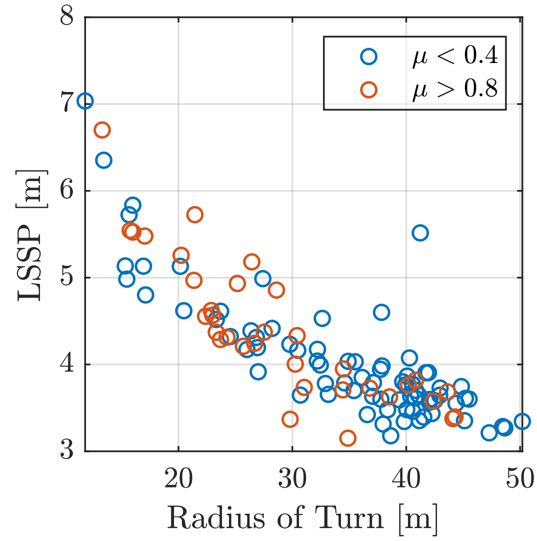
Figure 8 illustrates the variation of LSSP with the radius of turn for both left and right turns in both Intersections I_1 and I_2 at both low and high friction conditions. Similar to the roundabout, the LSSP decreases with the radius of turn. The LSSP in the left turns for a given instantaneous radius is slightly higher than it is in the right turns. This is true for both intersections. The reason can be attributed to the sharpness of the left turns in the intersections compared to the right turns. Furthermore, the difference in LSSP for a given instantaneous radius between two friction levels is insignificant.



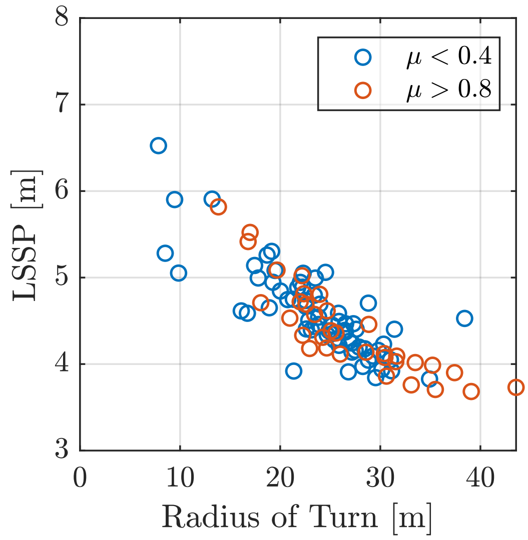
(a) I$_1$: Left turns



(b) I$_1$: Right turns



(c) I$_2$: Left turns



(d) I$_2$: Right turns

Figure 8 – LSSP in the intersections for left and right turns in I$_1$ and I$_2$.

7. Comparison with previous research

Bruzelius et al. (2021) performed full vehicle simulations with an A-double combination to investigate the influence of tire-road friction on low-speed offtracking. The simulations were conducted for roundabout manoeuvres with different exit angles (90, 120, 150, 180, 210 deg). The exit angle relevant to this paper is 90 deg as it closely resembles left and right turns in the intersections. For this exit angle, it was found that there is less than a 1% difference in low-speed offtracking between low and high-friction conditions. This is consistent with the observation made in this paper that friction conditions seem to have an insignificant impact on the LSSP.

8. Conclusions and future work

This paper evaluates the impact of tire-road friction on A-double's performance in roundabouts and intersections. Moreover, the speed chosen by the driver at different friction levels is also investigated in this paper.

Based on the analysed cases, it can be concluded that tire-road friction has a negligible effect on the swept path at low-speed manoeuvres like roundabouts and intersections. However, the driver's response in roundabouts is notably influenced by friction, with speed reductions observed in low-friction conditions before entering. Interestingly, this behaviour is not consistently observed at intersections, possibly due to the influence of surrounding traffic.

Since the road on which the A-double is driven is a single-lane road, lane changes are rare. Hence, the analysis in this paper did not include them. Future work could focus on investigating the effect of tire-road friction on the performance at high-speed manoeuvres like lane change. Additionally, a detailed analysis of traffic density is needed to understand the impact of friction on the driver response at the intersections.

9. Acknowledgements

The authors would like to thank Sweden's innovation agency, Vinnova, for financing this project (grant number 2021-05027). The authors are also grateful to Volvo Trucks for collecting the data for this project, and to researchers at Luleå University for estimation of tire-road friction.

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11. Appendix

Figure 9 shows the dimension of the A-double used in this study. The vehicle is driven empty from Piteå to Harbour with one of the tractor's rear axles lifted. Two typical full load cases, corresponding to the travel from Harbour to Piteå are provided in Table 1. Moreover, the tire specifications are presented in Table 2.

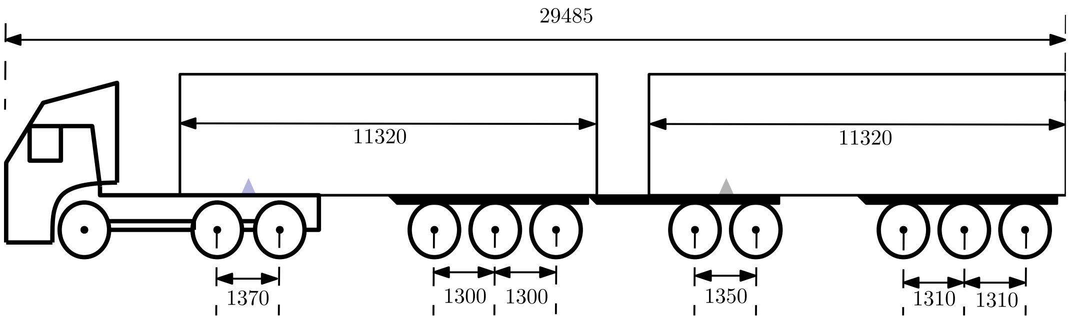

Figure 9 – Dimensions (in mm) of A-double.

Table 1 – Axle load specifications of A-double.

Case	**Tractor front (Tonnes) One axle**	**Tractor rear (Tonnes) Two axles**	**Semitrailer (Tonnes) Three axles**	**Fulltrailer front (Tonnes) Two axles**	**Fulltrailer rear (Tonnes) Three axles**	**Total (Tonnes)**
Empty (Piteå-harbour)	5.8	7 (one axle lifted)	3.4	4	3.9	24.1
Full load case 1 (Harbour-Piteå)	7.1	17	20.7	16.2	20.4	81.4
Full load case 2 (Harbour-Piteå)	7.1	18.4	23.4	17.8	21.6	88.3

Table 2 – Tire specifications of A-double.

	Tractor front One axle	**Tractor rear Two axles**	**Semitrailer Three axles**	**Fulltrailer front Two axles**	**Fulltrailer rear Three axles**
Tire	385/65X22.5	315/70X22.5	265/70X19.5	265/70X19.5	265/70X19.5
Driven	Hydraulic at low speed	Mech second declutchable	-	-	-
Pressure summer	8-9 bar	7-8 bar	7-8 bar	7-8 bar	7-8 bar
Winter	Studded tire	Snow tire	Snow tire	Snow tire	Snow tire
Pressure winter	8-9 bar	7-8 bar	7-8 bar	7-8 bar	7-8 bar