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RELIABILITY OF VEHICLE MOVEMENT SIMULATION RESULTS IN ROUNDABOUT DESIGN PROCEDURE BASED ON THE RULES OF DESIGN VEHICLE MOVEMENT GEOMETRY

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Abstract

Previous studies have shown that a valid roundabout design approach should include a determination of design elements based on the position of design vehicle's movement trajectories obtained by swept path analysis in early project stages, and not a conduction of swept path analysis at the end of design process. Several software which enable such significant progress in the design practice (optimal design of roundabout elements based on the results of vehicle movement simulation) are currently available on the market. Consequently, it is of great importance to know their accuracy. The reliability of vehicle movement simulation results is usually verified by field tests in which the distances between the test vehicle's movement trajectories are measured by means of a meter, which is a dilatory and time-consuming process. Within the scope of this study, a new approach for determination of the position of test vehicle's movement trajectories at the test site using a precise GNSS (Global Navigation Satellite System) device is described. The test vehicle was conducting a critical manoeuvre (left turn for 270°) for ten times, and the distances between its movement trajectories were determined by means of a meter and a precise GNSS device. The situation on the test site was then simulated on a computer and the assessment of the accuracy of chosen software for vehicle movement simulation was made.

Keywords: roundabout, swept path analysis, vehicle movement simulation, real drives, GNSS device, comparison

1 Introduction

According to existing roundabout design guidelines, roundabout planning and designing is an iterative procedure consisting of three main steps: (1) one of the available roundabout types is chosen depending on traffic conditions (e.g. single-lane roundabout, two-lane roundabout, turboroundabout); (2) the elements of the chosen roundabout type are designed in accordance with design rules (approaches, circulatory roadway, central island); (3) when all roundabout elements are designed, horizontal swept path and fastest path vehicle speed analyses are carried out [1-8]. If the analyses show that applied elements do not fulfil the swept path and/or speed requirements a redesign of roundabout elements is required. Main disadvantages of this procedure are reflected in the following: the design solution which fulfils the swept path and speed requirements is adopted and no further optimization of the design elements is made; detailed instructions on assigning input parameters for the swept path testing procedure are not provided, so the designer may come to the conclusion that the applied elements are successfully designed if the design vehicle in a simulated drive

passes through the roundabout along the arbitrarily selected path in any way (drive with difficulties or with extra space for unhindered movement) [9]. In the light of the above, this design procedure can lead to oversized or undersized roundabout solutions i.e. low capacity, poor traffic safety, low driving comfort, and high construction costs [10].
Long term studies performed at the Department for Transportation of Faculty of Civil Engineering, University of Zagreb [10-15] have shown that a valid roundabout design approach should include a determination of design elements based on the position of design vehicle's movement trajectories obtained by swept path analysis in early project stages, and not a conduction of swept path analysis at the end of design process - such an approach ensures the usage of optimal roundabout element dimensions and an unhindered path for the design vehicle through the intersection. Thereby, the design vehicle's swept path becomes a key factor in the roundabout geometric design [16]. Several software which enable such significant progress in the design practice (optimal design of roundabout elements based on the results of vehicle movement simulation) are currently available on the market [17-19]. Consequently, it is of great importance to know their accuracy.
The reliability of vehicle movement simulation results is usually verified by field tests in which the distance between the test vehicle's movement trajectories is measured by means of a meter. This is a quite dilatory and time-consuming process which requires a large number of participants in field tests and leads to a rather demanding subsequent data analysis on computer [20]. In this study, a new approach for determination of the position of test vehicle's movement trajectories at the test site using a precise GNSS (Global Navigation Satellite System) device is proposed. The main assumption was that the use of this precise GNSS device would greatly speed up and facilitate the previously described process.

2 Methods

In traffic networks in suburban areas where different types of roundabouts are usually planned (single-lane roundabouts, two-lane roundabouts, turboroundabouts etc.) a significant number of heavy vehicles (truck-semitrailer combinations and trucks with trailers) and intercity buses (two- and three-axle buses) is present [9]. Therefore, these are the groups of vehicles from which the least favourable one regarding swept path width is chosen as a design vehicle when suburban roundabouts are designed [1-8]. Due to limited financial resources, field tests described in this paper were conducted using only one of the aforementioned vehicles. This vehicle was a two-axle truck IVECO STRALIS 460 EEV EURO 5 with a three-axle semitrailer KRONE SDP 27 ELB4-CS shown in Figure 1.
As stated in Introduction, the distance between the test vehicle's movement trajectories was observed in this research. These movement trajectories are a path of front overhang, which is defined by the front most prominent point of the test vehicle, and a path of right rear overhang, which is defined by the inner endpoint of the test vehicle (Figure 2) [21].

Figure 1 Test vehicle used in the research

Figure 2 Water tanks at front most prominent point and inner endpoint of the test vehicle

Before the test drives begun, a path consisting of a 40 m long entry straight, a 58.9 m long circular arc with radius of 12.5 m, and a 40 m long exit straight (which represented a critical manoeuvre i.e. left turn for 270°) was marked at the pavement using a reinforced adhesive tape and a marking spray (Figure 3). The test vehicle followed this marked path for ten times with its front most prominent point, and its movement trajectories were drawn by a water traces drained through the thin pipes from the water tanks installed at its front most prominent point and the inner endpoint (Figure 4).

The distances between the test vehicle's movement trajectories, i.e. test vehicle's swept path widths w_i, were determined by means of a meter and a precise GNSS device Trimble R8 [22] in 32 cross sections after each drive (Figure 4). Consequently, the 320 swept path widths wi were determined by means of previously described procedures (Figure 5). However, the use of a precise GNSS device proved to be significantly faster and less demanding method for determining so many swept path widths wi compared to a meter.

It is important to stress that these field tests were conducted in the spring period when weather conditions were favourable: the day was sunny, there was no wind, and the air temperature ranged from 15°C to 20°C. Such weather conditions were required in order to prevent the water traces from drying during the measurements of vehicle's swept path widths after each drive.

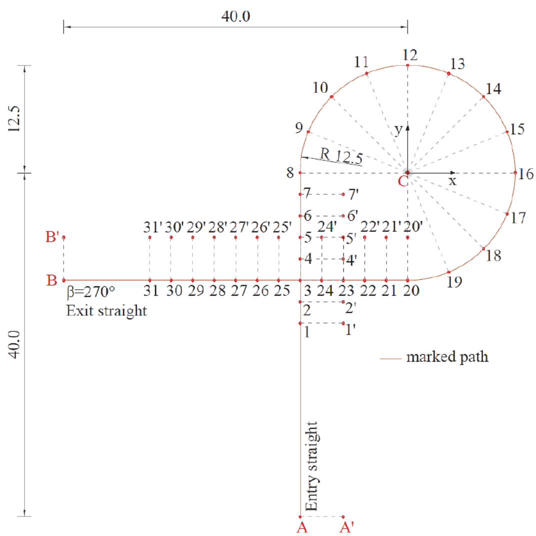

Figure 3 Elements of the path marked at the pavement and 32 cross sections in which the design vehicle's swept path widths wi were measured

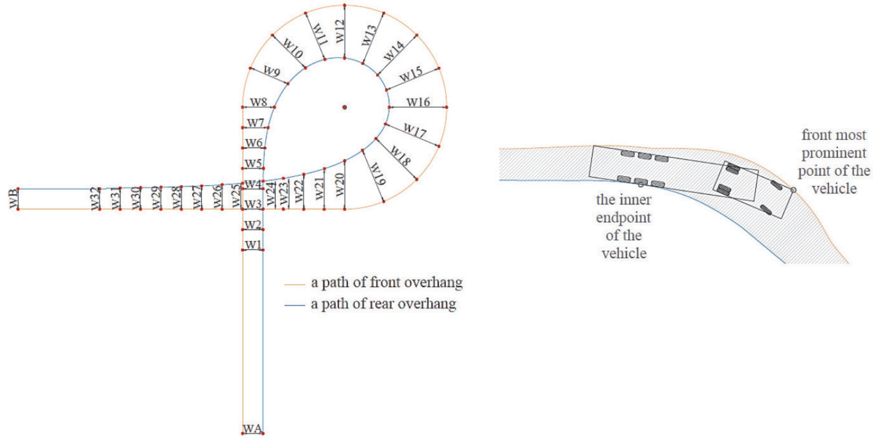

Figure 4 Movement trajectories and most prominent points of the test vehicle used in the research

Furthermore, it should be noted that this was not the first field test of this kind carried out by the research team from the University of Zagreb i.e. several trial tests were conducted in order to define the optimal measuring procedure which will result in high-accuracy data collection obtained by a dual-frequency GNSS device. GNSS observations were conducted using the high-precision real-time positioning service provided by the Croatian national network of continuously operating reference stations CROPOS (Croatian Positioning System). The obtained test vehicle's movement trajectories were referenced to the ETRS89 (European Terrestrial Reference System 1989) i.e. to the GRS80 ellipsoid (Geodetic Reference System 1980). The change of test vehicle's positions was captured by the single-epoch measurements at 32 cross-sections with the position precision expressed by the standard deviation of 0.56 cm. All measurements were checked for the outliers.

Figure 5 Test drive and measurements of test vehicle's swept path widths

3 Results of field tests

The analysis of data obtained by field tests was carried out using the Autodesk AutoCAD software. Firstly, the path that test vehicle followed, the 32 cross sections in which swept path widths were measured, and the test vehicle's movement trajectories were positioned using the geo-referenced points obtained by a precise GNSS device at the test site. All these elements (the path, the cross sections, and the test vehicle's movement trajectories) were then approximated with AutoCAD's cubic splines, i.e. interpolation polynomials of the third degree. Finally, the test vehicle's swept path widths w_i in 32 cross sections were measured and compared with those determined by means of a meter (Figure 6). Following conclusions were made based on this comparison:

• while conducting a critical maneuver, the test vehicle occupied the largest surface at the very end of the circular part of the path (cross section no. 18);
• the average difference between the swept path widths determined by means of a meter and the swept path widths determined by means of a precise GNSS device (in all cross sections and for all test drives) amounted +1 cm.

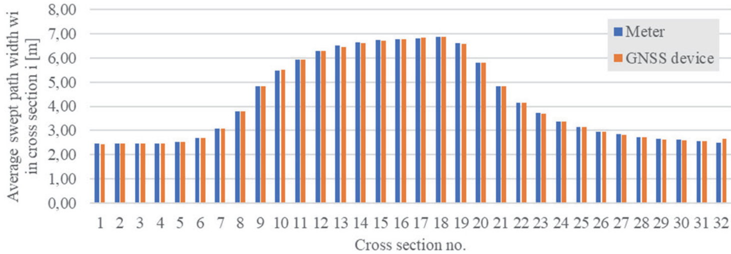

Figure 6 Results of field tests

Accordingly, measuring using a precise GNSS device is not only a fast, but also, a very precise method for determining the test vehicle's swept path widths at the test site. Moreover, the data obtained by this precise GNSS device is a rather simple to analyse.

4 Vehicle movement simulation

After the accuracy of results of field testes obtained by a precise GNSS device was confirmed, the situation on the test site was simulated in Autodesk's Vehicle Tracking software. Firstly, a virtual vehicle with dimensions equal to those of the test vehicle used in the field tests was created. The exact dimensions of the test vehicle were determined based on the data provided in catalogues of its manufacturers [23-24] and checked by hand measurements with a meter after the field tests finished (Figure 7).
This virtual vehicle followed the test vehicle's outer movement trajectories obtained by a precise GNSS device at the test site (outer cubic splines), and the swept path widths obtained by vehicle movement simulation and real drives were compared. Finally, the assessment of the accuracy of Vehicle Tracking software for vehicle movement simulation was made.

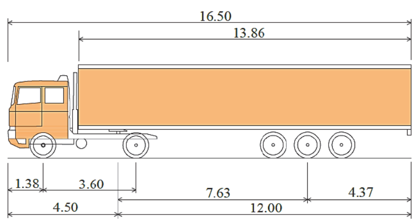

Figure 7 Dimensions of the test vehicle

4.1 A comparison of simulated and real swept paths

A comparison between the swept path widths determined by means of a vehicle movement simulation and the swept path widths determined by means of a precise GNSS device at the test site is given in Figure 8. Following conclusions have been made:
• largest differences between the swept path widths obtained by vehicle movement simulation and the swept path widths obtained by real drives occurred at the very beginning of vehicle's path (cross section no. 1) and amounted up to +12 cm;

- the average difference between swept path widths obtained by vehicle movement simulation and real drives (in all cross sections and for all test drives) amounted +7 cm;
- the simulation resulted in greater swept path widths in 95 % of cases, which is favourable in terms of roundabout planning.

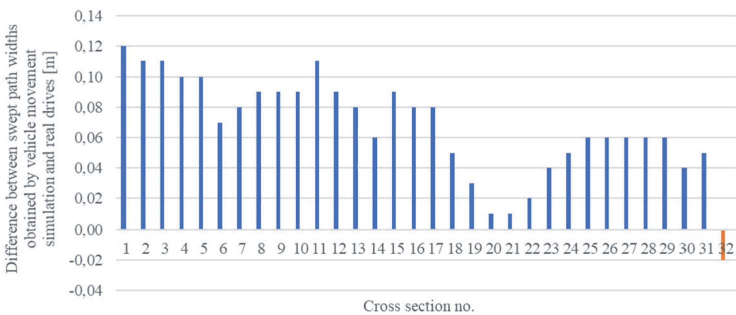

Figure 8 The differences between the swept path widths determined by means of a vehicle movement simulation and the swept path widths determined by means of a precise GNSS device at the test site

4.2 Assessment of the reliability of chosen software for vehicle movement simulation

The reliability of chosen software for vehicle movement simulation has been evaluated using the T-test for the significance of the difference between the means of two independent samples. The null hypothesis H_0 was as follows: the swept path widths determined by field measurements μ_0 are equal to swept path widths determined by vehicle movement simulation μ_1 (Equation 1). The alternative hypothesis H_1 was: the swept path widths determined by field measurements μ_0 differ from swept path widths determined by vehicle movement simulation μ_1 i.e. one method resulted in greater swept path widths than the other (Equation 2). The significance level was $\alpha = 0.05$.

$$H_0 : \mu_0 = \mu_1 \tag{1}$$

$$H_0 : \mu_0 \neq \mu_1$$
$$H_0 : \mu_0 > \mu_1 \tag{2}$$

T-test for 95 % confidence interval has shown that the swept path widths determined by field measurements are equal to the swept path widths determined by vehicle movement simulation. As shown in Table 1, p-values were greater than the significance level α in the case of all test drives.

Table 1 T-test results

Result	Test drive no.									
	1	2	3	4	5	6	7	8	9	10
p-value	0.435	0.431	0.435	0.434	0.439	0.426	0.450	0.447	0.463	0.422

Normality of average differences between the swept path widths determined by field measurements and swept path widths determined by vehicle movement simulation was tested using the Shapiro-Wilk's and QQ tests.
The null hypothesis H_0 in the Shapiro-Wilk test was that the distribution of these average differences is normal (Equation 3) and the alternative hypothesis H_1 that the distribution is not normal (Equation 4). The significance level was α = 0.05.

$$H_0 : \mu_0 = \mu_1 \tag{3}$$

$$H_0 : \mu_0 \neq \mu_1 \tag{4}$$

Shapiro-Wilk test for 95 % confidence interval has shown that the distribution of average differences between the swept path widths determined by field measurements and vehicle movement simulation is normal (p-value amounted 0.370) (Figure 9).

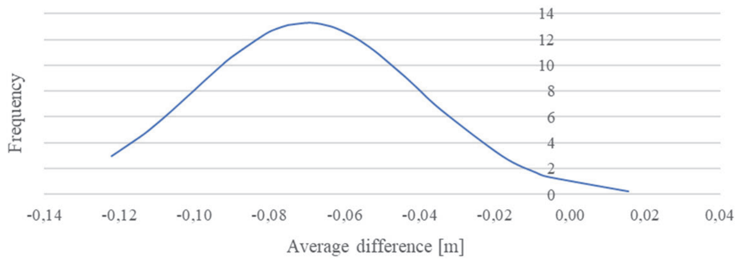

Figure 9 Normal distributions of average differences between swept path widths obtained by field measurements and vehicle movement simulations

Above results were confirmed by the results of QQ test (Figure 10). The linearity of the points suggests that the analysed data are normally distributed.

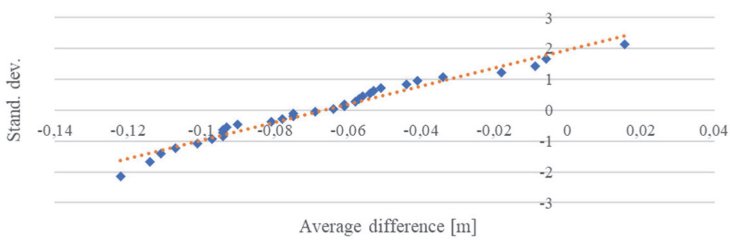

Figure 10 Results of QQ tests

5 Conclusions

A valid roundabout design approach should include a determination of design elements based on the position of the design vehicle's movement trajectories obtained by swept path analysis, and not a conduction of swept path analysis at the end of design process. Thereby, the design vehicle's swept path becomes a key factor in roundabout geometric design.
The reliability of software for vehicle movement simulation, which enables such significant progress in the design practice, is usually verified by field tests in which the distance between the test vehicle's movement trajectories is measured by means of a meter. However, the results of field tests carried out within the scope of this research have shown that the use of a precise GNSS device significantly simplifies and speeds up this process and therefore

leads to a lower total costs of field tests (lower rental costs of test polygons, lower rental costs of test vehicles, lower driver service costs). Moreover, this testing approach requires fewer people to participate in the field surveys and facilitates the subsequent analysis of test results on a computer.

A comparison of swept path widths determined by means of vehicle movement simulation in Autodesk's Vehicle Tracking software and real swept path widths determined by means of precise GNSS device at the test site has shown the following:

- the simulation results in greater swept path widths in 95 % of cases, which is favourable in terms of roundabout planning;
- from a statistical point of view these swept path widths do not differ.

In view of the above, the procedure described in the paper could be used, not only in the assessment of the reliability of one software for vehicle movement simulation, but also in the definition of the optimal software for vehicle movement simulation depending on the chosen design vehicle and intersection type.

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