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Functions, Capacities, and Traffic Safety Characteristics of Some Types of Two-Level Roundabouts

Tomaž Tollazzi [1], Marco Guerrieri [2], Goran Jovanović [3] and Marko Renčelj [1,*]

[1] Faculty of Civil Engineering, Transportation Engineering and Architecture, University of Maribor, Smetanova ul. 17, SI-2000 Maribor, Slovenia; tomaz.tollazzi@um.si
[2] Department of Civil, Environmental and Mechanical Engineering, University of Trento, Via Mesiano 77, 38123 Trento, Italy; marco.guerrieri@unitn.it
[3] Independent Researcher Appia Ltd., Leskoškova c. 9e, SI-1000 Ljubljana, Slovenia; goran.jovanovic@appia.si
* Correspondence: marko.rencelj@um.si; Tel.: +386-2-229-43-72

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Abstract: Over recent decades, roundabouts have become increasingly used when building new at-grade intersections or up-grade junctions all over the world. Consequently, control of traffic flows at at-grade intersections and up-grade junctions using roundabouts creates unique design problems. Nowadays, 'alternative' types of roundabouts have started to become very popular, especially because of their advantages compared with 'standard' roundabouts and standard types of up-grade junctions. Some of these alternative types of roundabouts are two-level roundabouts, which are still currently in the development phase. It is for this reason that they can be called 'theoretical roundabouts'. Two-level roundabouts are particularly useful in urban and suburban areas with space limitations due to their relatively small footprint. This paper illustrates three new alternative types of two-level roundabouts—'target', 'four flyover', and 'roundabout with left and right bypasses'—as well as their functions, capacities, and traffic safety characteristics.

Keywords: two-level roundabouts; target roundabout; four flyover roundabout; roundabout with left and right bypasses; function; capacity; traffic safety characteristics

1. Introduction

A growing number of foreign studies have pointed out the poor traffic safety characteristics of 'standard' two-lane roundabouts and a lower capacity than what was expected [1]. These problems are resolved in various ways in different countries [2]; however, it seems that the best way is to decrease the number of conflict spots [3], which is one of the main characteristics of 'alternative' (or unconventional) types of roundabouts. Some alternative types of roundabouts are already in frequent use all over the world, other types have only been implemented within certain countries, while some are still in the development phase [4] and, hence, can be called 'theoretical roundabouts'.

Some of these 'theoretical roundabouts' are two-level roundabouts, which are still in the development phase. Two-level roundabouts are useful in suburban areas with plenty of space, where two-level interchanges (standard diamond, diverging diamond, cloverleaf interchange) are possible solutions. However, two-level roundabouts are particularly useful in urban areas with space limitations due to their relatively small footprint.

The purpose of this paper is to present three types of roundabouts ('target', 'four flyover', and 'roundabout with left and right bypasses'). Although we are living in a 'global world', it usually takes a couple of years for the wider population to become familiar with this type of information.

Consequently, there is a significant probability that there are actually more unknown 'theoretical' two-level roundabouts.

2. Basic Characteristics and Design Elements of 'Target', 'Four Flyover', and 'Roundabout with Left and Right Bypasses'

2.1. 'Target' Roundabout

The 'target' roundabout [5] is designed as two one-lane roundabouts with different outer diameters located on dual levels (Figure 1), and all vehicles turning right at both roundabouts have their own separate right-hand-turn bypass lanes. This type of roundabout allows one to drive from all directions to all directions, and if someone makes an error, e.g., if a driver mistakenly stays in the left-hand lane at the entrance, it is still possible to turn right at the next exit (which is not the case for the turbo roundabout).

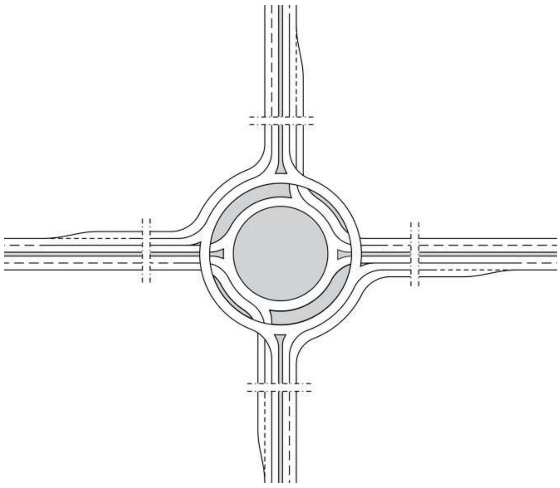

Figure 1. Typical layout of a 'target' roundabout.

The geometrical form of the 'target' roundabout is somewhat simpler than that of the turbo roundabout. A 'target' roundabout is designed as a double roundabout with different outer diameters (D_{outer} = 51 m and d_{outer} = 29 m, respectively) located on two different levels, and all vehicles turning right in both roundabouts have their own separate right-hand-turn bypass lanes ($D_{bypasses}$ = 61 m, $d_{bypasses}$ = 39 m).

The basic characteristics of the 'target' roundabout are similar to those of the turbo roundabout: physically separated traffic lanes within a circulatory carriageway, bypasses, and one-lane circulatory roadway sections. All vehicles turning right have their own separate traffic lanes; consequently, the inner circulatory roadway is used only by vehicles that drive through a roundabout, drive for three-quarters of the circle, or drive in a semicircle. In a 'target' roundabout, the circulating flow in front of each entry is lower than that in the standard two-lane and turbo roundabouts [6]. Driving in a 'target' roundabout is the same as for a turbo roundabout, with the same signposting and lane markings.

2.2. 'Four Flyover' Roundabouts

The roundabout with separate left-hand-turn bypasses on major roads—in short, the 'four flyover' roundabout (Figure 2)—is designed with one large one-lane roundabout on an upper level, and vehicles turning left on major roads have their own separate left-hand-turn bypass lanes located on another lower level. Vehicles turning left are located as they are in standard at-grade intersections, i.e., in the left lane on the approach.

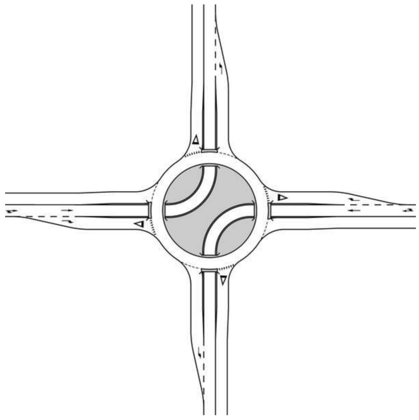

Figure 2. A roundabout with segregated left-hand-turn bypasses on major roads: the 'four flyover' roundabout.

'Four flyover' roundabouts are designed with one large one-lane roundabout (D_{outer} = 80 m) on the upper level, and all vehicles turning left on major roads have their own separate left-hand-turn bypass lanes (R = 35 m) located on another lower level.

By physically separating left-hand turning traffic flow on major roads, a one-lane roundabout is obtained, with no crossing and weaving conflict spots.

2.3. Roundabout with Left-Hand and Right-Hand Bypasses

The roundabout with segregated left-hand-turn bypasses on major roads and right-hand-turn bypasses on minor roads—in short, the 'flyover plus' roundabout (Figure 3)—is a variation of the 'four flyover' roundabout. It is also a hybrid, similar to the 'four flyover roundabout', and it combines a one-lane roundabout, right-hand-turn bypasses, and left-hand-turn bypasses located on another lower level.

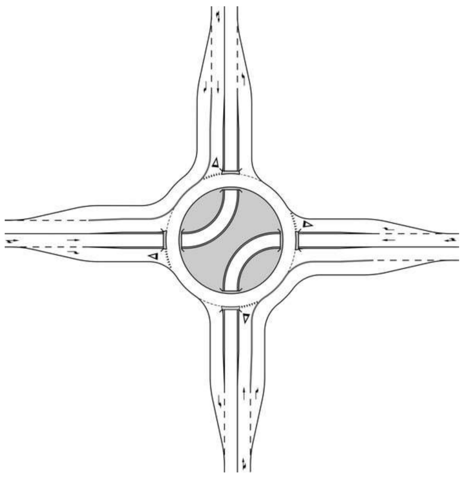

Figure 3. Roundabout with left-hand and right-hand bypasses ('flyover plus' roundabout).

This type of roundabout is designed as one large one-lane roundabout (D_{outer} = 80 m) on one level, and all vehicles turning left on major roads have their own separate left-hand-turn bypass lanes (R = 35 m) located on another lower level. Bypasses for right-hand turns are added on minor roads (D_{outer} = 90 m).

3. Capacity Characteristics of Two-Level Roundabouts

To determine the measures of effectiveness (MOE) of two-level roundabouts, a microsimulation software tool (VISSIM) was chosen, which is usually employed to analyze innovations in the fields of at-grade intersections and up-grade interchanges.

This microsimulation software tool is ideal for setting up a clear and conclusive knowledge basis for decisions regarding all kinds of traffic engineering questions. The system has been designed for analyzing and modeling transport networks of any size, and traffic systems of all types, from individual intersections to entire conurbations.

The link-connector structure of this network topology allows for the highest versatility and, in combination with detailed movement models, extremely precise traffic flow modeling.

Capacities were estimated by means of the delays, evaluated under numerous traffic conditions, and were characterized by three traffic distribution test matrices (Equations (1)–(3)): ρ_1 (70% of entry traffic crossed the roundabout), ρ_2 (70% of traffic turned left), and ρ_3 (70% of traffic coming from every direction turned right). Three different traffic demand scenarios were used: 750, 1500, and 2250 veh/h). All scenarios are arranged in such a way that 67% of the traffic on the major road and 33% of the traffic on the minor road. The types of vehicles observed in microsimulations were passenger cars (98%) and semi-trailers (2%).

Origin/destination (O/D) matrices of traffic flow distributions in percentage terms are shown in Equations (1)–(3).

$$\rho_1 = \begin{bmatrix} 0 & 0.15 & 0.70 & 0.15 \\ 0.15 & 0 & 0.15 & 0.70 \\ 0.70 & 0.15 & 0 & 0.15 \\ 0.15 & 0.70 & 0.15 & 0 \end{bmatrix} \quad (1)$$

$$\rho_2 = \begin{bmatrix} 0 & 0.15 & 0.15 & 0.70 \\ 0.70 & 0 & 0.15 & 0.15 \\ 0.15 & 0.70 & 0 & 0.15 \\ 0.15 & 0.15 & 0.70 & 0 \end{bmatrix} \quad (2)$$

$$\rho_3 = \begin{bmatrix} 0 & 0.70 & 0.15 & 0.15 \\ 0.15 & 0 & 0.70 & 0.15 \\ 0.15 & 0.15 & 0 & 0.70 \\ 0.70 & 0.15 & 0.15 & 0 \end{bmatrix} \quad (3)$$

The following assumptions were used:

- since the roundabouts presented in this paper only exist in the development stage, no real situations can be observed to calibrate and validate the microsimulation according to validation standards (DMRB 12, GEH statistics);
- the vehicle speed, acceleration, and deceleration at the roundabouts were modeled according to previous research and measurements [7];
- the gap acceptance model was used at the entry of roundabouts to define the right-of-way by using the same parameters (critical gap, follow-up time, etc.) for all the analyzed scenarios;
- the topology of the modeled area used was flat (no additional influence due to acceleration/deceleration);
- the performance of the geometry of the chosen roundabouts was evaluated according to several MOE, such as delay, queue, and number of stops;
- the calculated values of average delay times, average length of queues, and average number of stops in the microsimulation were recorded every 900 s on all roundabout lanes and summarized for a one-hour simulation period; and
- the level of service was calculated according to the Slovenian Technical Regulation for Design projects for roads (HCM LOS standards [8]).

3.1. 'Target' Roundabout

The major flow in the roundabout was oriented to N–S (see Figure 1).

Figure 4 (average delay time) and Figure 5 (length of queues) show a load scenario of 2250 veh/h (total 4500 veh/h), which resulted in the highest delays in traffic distribution ρ_2 (70% of traffic turned left). Vehicles entering the roundabout on two lanes needed to change lanes before entering the roundabout, which resulted in delays and queues being formed. Comparable results were achieved for traffic distribution ρ_1 (70% of traffic passed through). In both traffic distributions the level of service was LOS = F. The level of service for traffic distribution ρ_3 was LOS = A. No delays were noticed, and there were minimal queues. The traffic flowed smoothly because there were two entering lanes and one direct right-hand turning lane.

Figure 4. 'Target' roundabout—average delay.

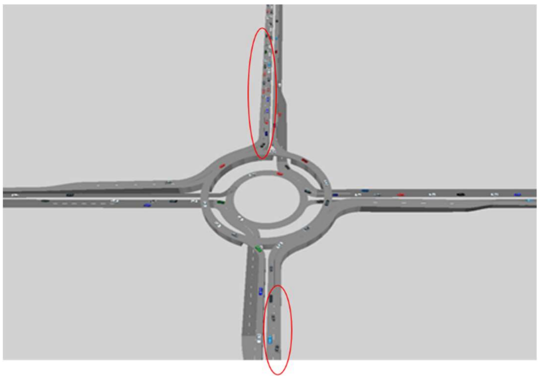

Figure 5. 'Target' roundabout—queue formations.

For the load scenarios with 1500 veh/h (total 3000 veh/h), only traffic distribution ρ_2 was not acceptable (LOS = F).

3.2. 'Four Flyover' Roundabouts

The major flow in this roundabout was oriented to E–W (see Figure 2). The scenario shown in Figures 6 and 7 with 2250 veh/h (total 4500 veh/h) caused the highest delays in traffic distribution ρ_1 (70% of traffic passed through). Vehicles entering the roundabout on one lane needed to give way to circulating flow, which caused delays and queues before entering the roundabout. Comparable results were achieved for traffic distribution ρ_2 (70% of traffic turned left). In both traffic distributions the level of service was LOS = F. The level of service for traffic distribution ρ_3 was LOS = E with a significantly shorter average queue length. For the load scenario 1500 veh/h (total 3000 veh/h), only traffic distribution ρ_3 was acceptable (LOS = B).

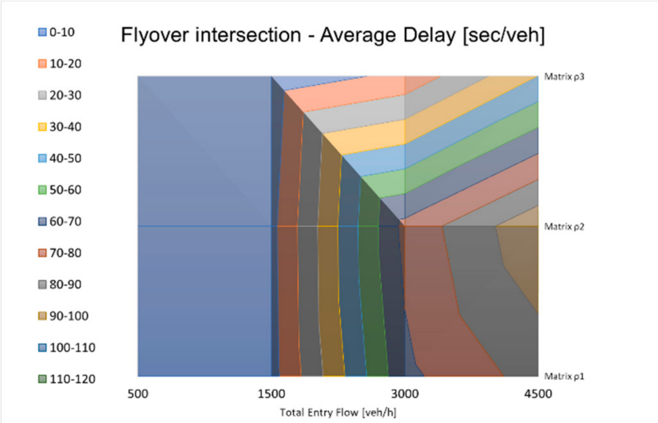

Figure 6. 'Four flyover' roundabout—average delay.

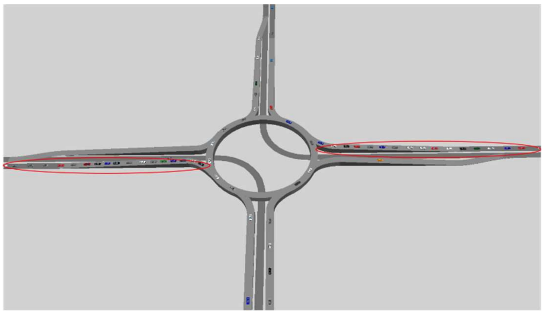

Figure 7. 'Four flyover' roundabouts—queue formations.

3.3. *Roundabout with Left and Right Bypasses*

The major flow in this roundabout was oriented to E–W (see Figure 3). This roundabout was very similar in design to the flyover roundabout with added bypasses. The scenario of 2250 veh/h (total 4500 veh/h) shown in Figures 8 and 9 caused the highest delay in traffic distribution ρ_1 (70% of traffic passed through). Vehicles entering the roundabout on just one lane needed to give way to circulating flow, which caused delays and queues before entering the roundabout. For traffic distribution ρ_2 (70% traffic turned left), significantly better performance was achieved (LOS = E) due to the exclusive and direct left lane. The level of service for traffic distribution ρ_3 (70% of traffic turned right) was LOS = D and had a significantly shorter average queue length. For the load scenario of 1500 veh/h (total 3000 veh/h), only traffic distribution ρ_1 was not acceptable (LOS = F), and all other load scenarios were acceptable (LOS = A).

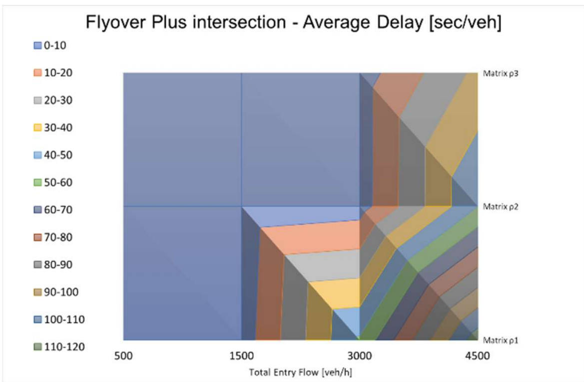

Figure 8. Roundabout with left-hand and right-hand bypasses—average delay.

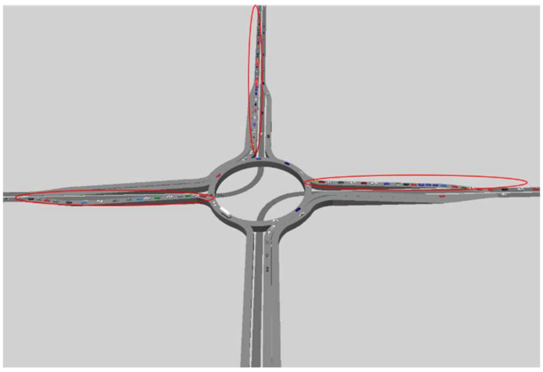

Figure 9. Roundabout with left-hand and right-hand bypasses—queue formations.

3.4. Comparison of Average Delays and Queues

The average delay and queue of each type of roundabout were calculated, and the results are shown in Figures 10–16. The 'target' roundabout lowered delays in traffic distributions ρ_1 and ρ_3. In traffic distribution ρ_2, the 'flyover plus' had a greater capacity in all the total entry flow scenarios. The reason lies in the design geometry, as left-hand turn lanes are exclusive. The best performances according to the demand and supply obtained for 'target' roundabouts for traffic distribution were ρ_1 and ρ_3. Only in traffic distribution ρ_3 was the supply equal to demand. The 'flyover plus' had the best performance according to the demand and supply for traffic distribution ρ_2 and almost fulfilled (4288 veh/h) the demand of the highest traffic level scenario of 4500 veh/h.

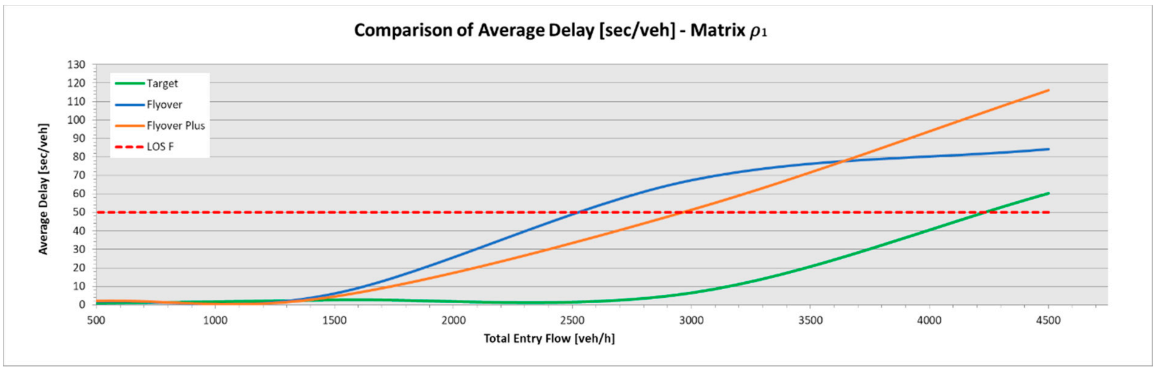

Figure 10. Average delay—matrix ρ_1.

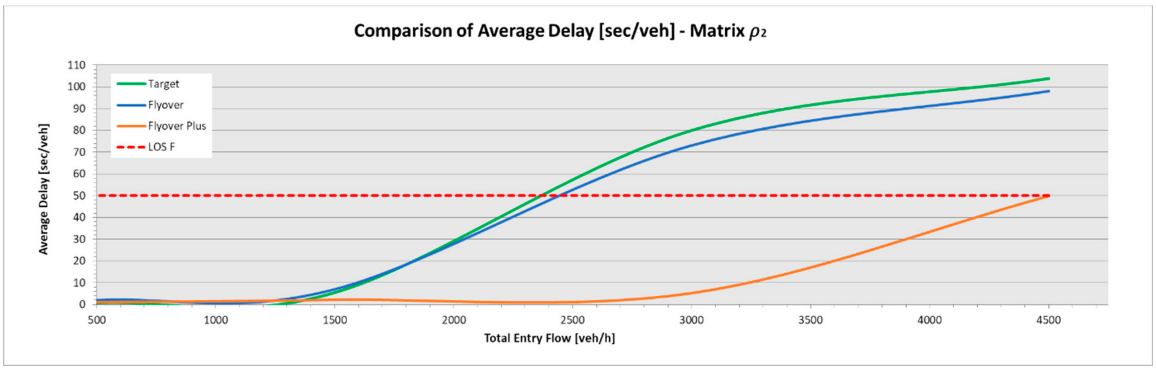

Figure 11. Average delay—matrix ρ_2.

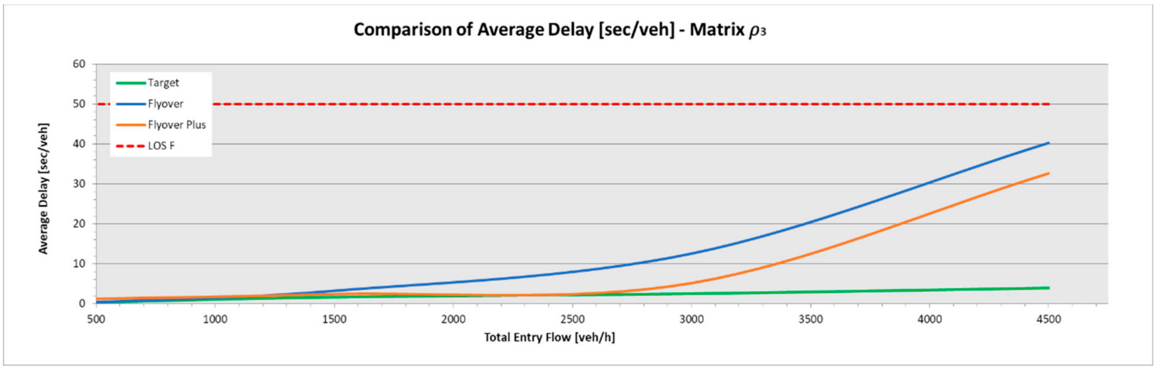

Figure 12. Average delay—matrix ρ_3.

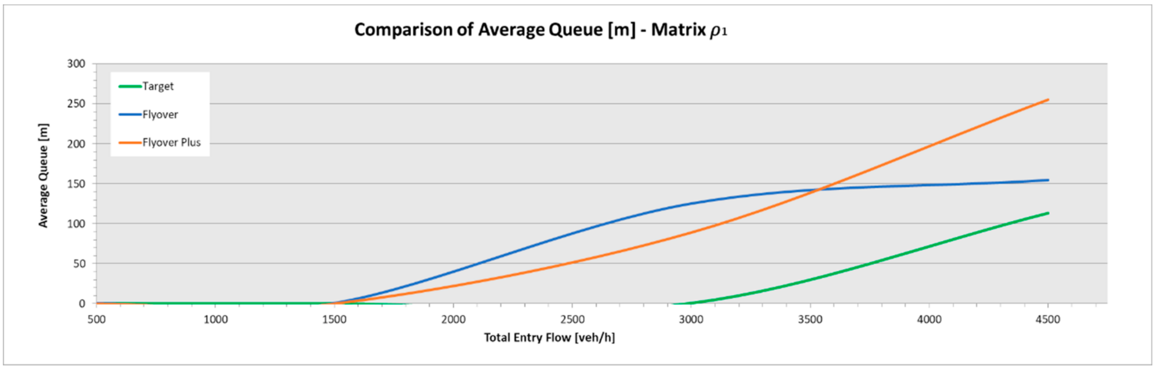

Figure 13. Average queue—matrix ρ_1.

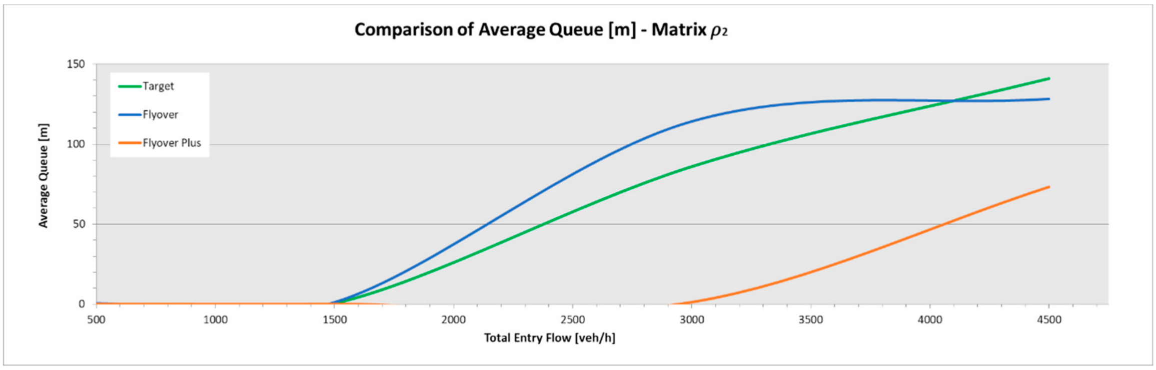

Figure 14. Average queue—matrix ρ_2.

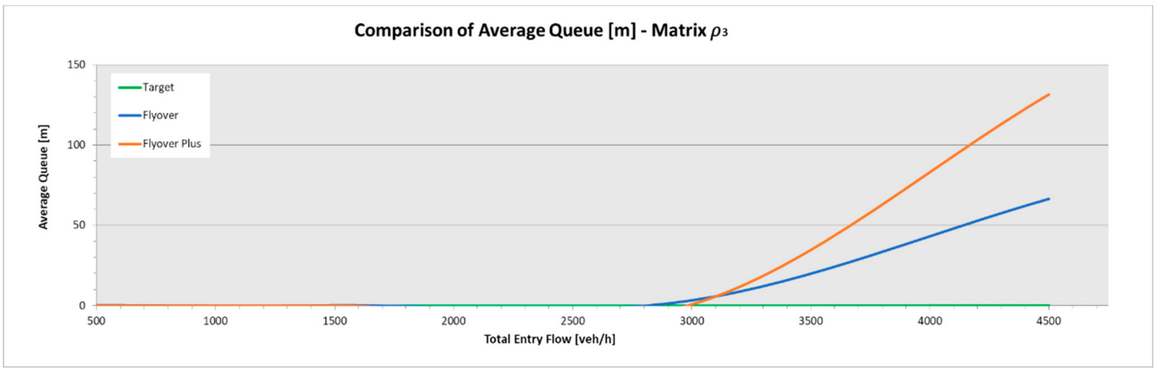

Figure 15. Average queue—matrix ρ_3.

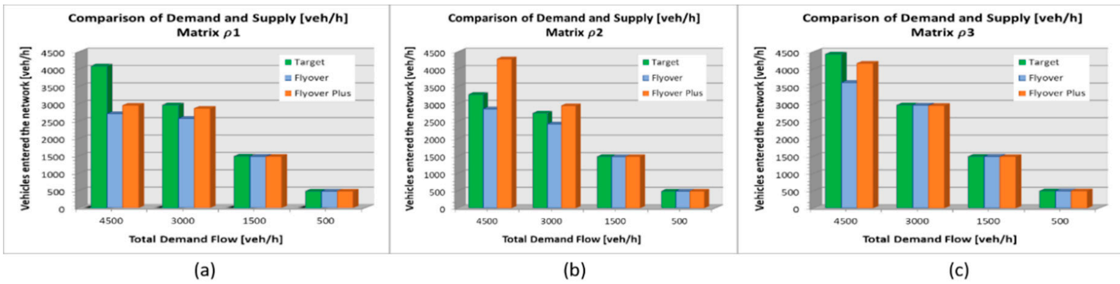

Figure 16. (**a**–**c**) Comparison of demand and supply.

4. Traffic Safety Characteristics

For the purpose of determining the proposed solutions from a traffic safety point of view, the software tool SSAM (Surrogate Safety Assessment Model [9,10]) was chosen, which is usually used to analyze innovations in the field of at-grade intersections and up-grade interchanges.

SSAM uses a technique that combines microsimulation and automated conflict analysis of vehicle trajectories. It analyzes the frequency and characteristics of narrowly averted vehicle-to-vehicle collisions in traffic, and it assesses the safety of traffic facilities without waiting for a statistically above-normal number of crashes and injuries to occur.

Microsimulations are typically performed for peak hours, while conventional crash prediction models used in safety management are used according to crashes per year as the dependent variable and AADT (annual average daily traffic) as the main independent variable [11]. The aim of this comparison was not to calculate the number of predicted crashes, but rather to compare potential conflicts during the peak traffic hour.

Analysis of conflicts was not carried out for all three traffic distribution matrices, but instead only for one (maximum) traffic flow strength (2250 veh/h). A simulation was run for each type of roundabout, and the results of these runs were used in a comparative analysis. The time to collision (TTC) used was 0.1 s < TTC < 1.5 s, while a post-encroachment time (PET) of 0.5 s < PET < 5 s was used. Conflicts with any values of TTC and PET equal to zero indicated possible errors in the simulation; therefore, those results were filtered out.

In terms of Figure 17a–c, it is possible to conclude that no crossing conflicts were identified in all three layouts. One of the reasons is the two-level layout of roundabouts; therefore, there were no conflict angles between 85° and 180°.

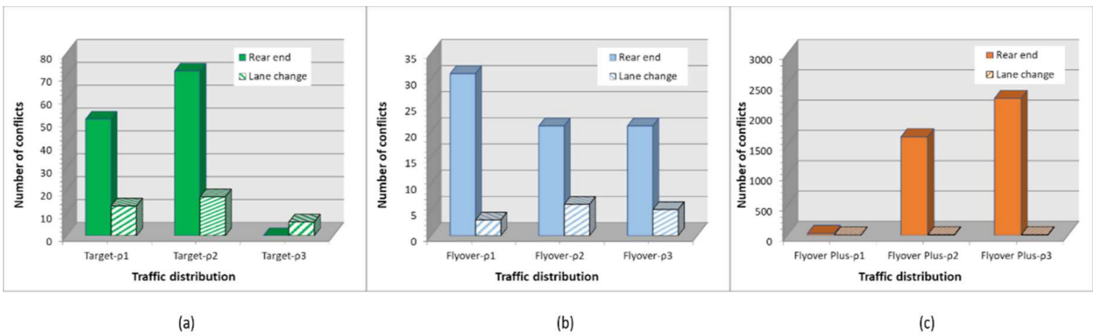

Figure 17. (**a**–**c**) Predicted conflicts by type for different layouts and traffic distributions.

The ‘flyover’ roundabout had the best safety performance, as shown in Figure 18 and graphically presented in Figure 19. ‘Flyover plus’ roundabouts generated the highest number of conflict spots, especially in the ρ_3 traffic distribution, which is also clearly visible in Figure 19.

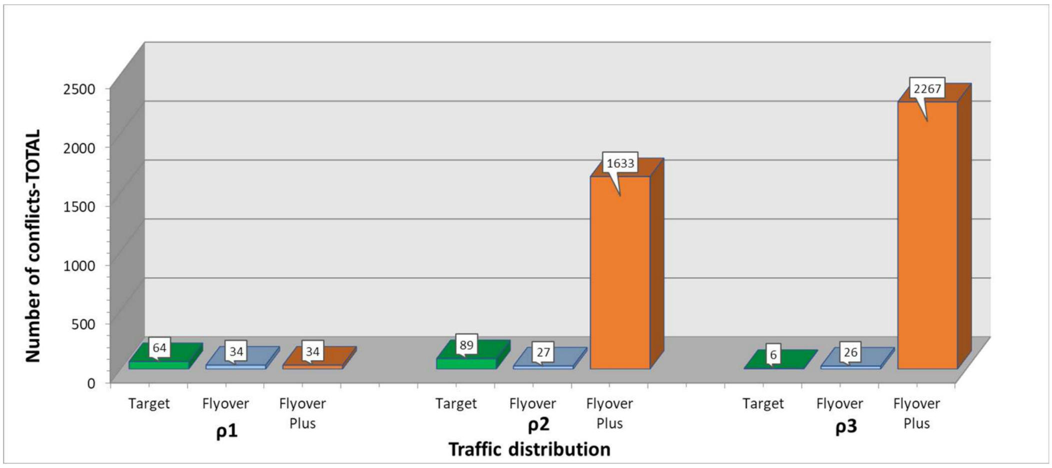

Figure 18. Total predicted conflicts for different layout and traffic distributions.

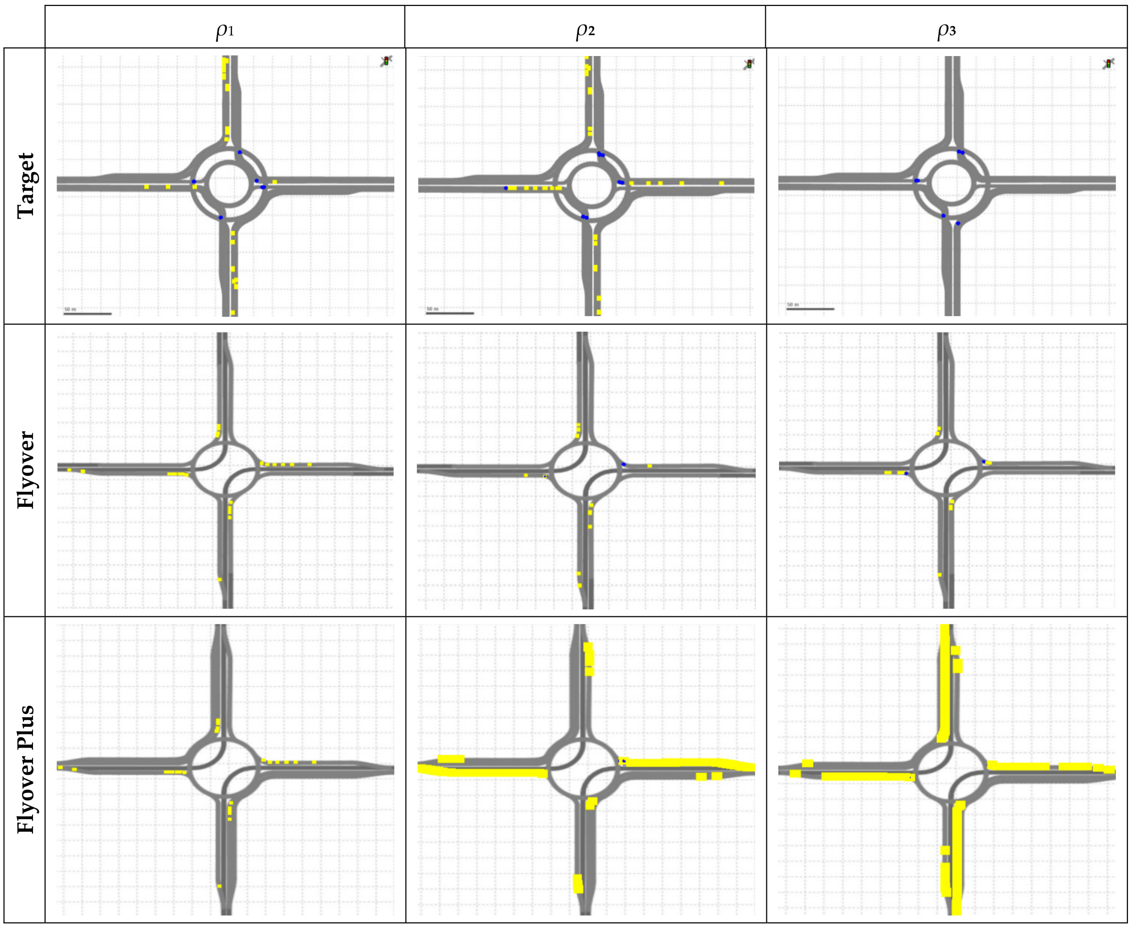

Figure 19. Predicted conflict identification for different layout and traffic distributions (yellow—rear end conflicts, blue—lane change conflicts).

'Target' roundabouts generated more conflicts for traffic distribution ρ_2, 'flyover' for traffic distribution ρ_1, while 'flyover plus' roundabouts generated more conflicts for traffic distribution ρ_3. The best safety performances of 'target' and 'flyover' roundabouts were obtained for traffic distribution ρ_3, while the 'flyover plus' was the safest under traffic distribution ρ_2.

The majority of conflicts were represented by rear-end collisions, which in real life are not fatal, especially at roundabouts where drivers are not speeding and the speed difference between two vehicles is much lower than on open road sections.

5. Conclusions

'Alternative' types of roundabouts are becoming very popular nowadays, especially because of their advantages compared to 'standard' roundabouts and standard types of up-grade junctions.

Some of these alternative types of roundabouts are two-level roundabouts, which are still currently in development phases. Two-level roundabouts are especially useful in urban and suburban areas that have limited space due to their relatively small footprint.

The purpose of this paper was to present three types of two-level roundabouts ('target', 'four flyover', and 'roundabout with left and right bypasses') as well as their functional, capacity, and safety characteristics.

Capacities were estimated by microsimulation. The delays, queues, and number of stops were evaluated under numerous traffic conditions, characterized by three traffic distribution test matrices—ρ_1 (70% of entry traffic crossed the roundabout), ρ_2 (70% of traffic turned left), and ρ_3 (70% of traffic coming from every lane turned right)—and for three different traffic demand scenarios (750, 1500, and 2250 veh/h). Since the roundabouts presented in this paper only exist in the development stage, no real situations can be observed to calibrate and validate the model according to validation standards (DMRB 12, GEH statistics).

Under the traffic demand scenario of 2250 veh/h (total 4500 veh/h), the 'target' roundabout caused the highest delays (LOS = F) in traffic distribution ρ_2 (70% of traffic turned left), while for the load scenarios of 1500 veh/h (total 3000 veh/h), only traffic distribution ρ_2 was not acceptable (LOS = F).

Under a traffic demand scenario of 2250 veh/h (total 4500 veh/h), the 'flyover' roundabout caused the highest delays (LOS = F) in traffic distribution ρ_1 (70% of traffic turned left), while for the load scenario of 1500 veh/h (total 3000 veh/h), the traffic distribution ρ_3 was also acceptable (LOS = B).

Under the scenario of 2250 veh/h (total 4500 veh/h), the 'flyover plus' roundabout caused the highest delays in traffic distribution ρ_1 (70% of traffic passed through). Vehicles entering the roundabout on just one lane need to give way to circulating flow, which causes delays and queues before entering the roundabout. For the load scenario of 1500 veh/h (total 3000 veh/h), only traffic distribution ρ_1 was not acceptable (LOS = F), while all other load scenarios were acceptable (LOS = A).

The performance indicators were calculated for all three layouts, and the average delay vs. total entry flow curves (Figures 10–12) and the queues vs. total entry flow curves (Figures 13–15) were developed.

It can be concluded that the 'target' roundabout had the highest capacity in ρ_1 and ρ_3 traffic distributions, while the 'flyover plus' was highest in terms of the ρ_2 traffic distribution.

For the purpose of determining the proposed solutions from a traffic safety point of view, the software tool SSAM (Surrogate Safety Assessment Model) was chosen, which is usually used to analyze innovations in the field of at-grade intersections and up-grade interchanges.

None of the three layouts generated any crossing conflicts. One of the reasons is because the two-level layout of roundabouts led to no conflict angles between 85° and 180°. The 'flyover' roundabout had the best safety performance, while the 'flyover plus' roundabout generated the highest number conflict points, especially in the ρ_3 traffic distribution.

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