SIMULATION OF A VEHICULAR TRAFFIC SYSTEM BASED ON QUEUEING NETWORK MODELS: COMPARATIVE ANALYSIS OF TWO MODELS

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Abstract: In the previous works we presented a study for modeling and simulation of vehicular traffic systems based on queuing networks. Specifically, in paper (Pasini and Bianchini, 2019), we studied the urban network located in North Siena, in the city of Siena (Italy), in its actual layout, after the Municipality had introduced some changes for vehicular flow management. This system is based on two roundabouts and a crossroad, as shown in Figure 1. In this work, we are going to conclude our previous study, comparing the actual vehicular flow and the flow derived from an alternative system, foreseen by the PRG of the Municipality of Siena which is composed of three roundabouts and which has not been implemented yet.

Keywords: vehicular traffic systems, queuing networks, modeling and simulation

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1. Introduction

The vehicular traffic flows of the North Siena urban road system in Siena, Italy, is studied in this work. The study focuses on analysis of the current traffic system which has recently been modified by the Municipal Administration, and on an alternative system that has been described in the PRG. In particular a comparison will be made between the levels of vehicular traffic congestion that occur in the two systems.

The study consists in simulating both traffic models to evaluate the impact of possible changes in the studied area of the city of Siena on the vehicular flow. With reference to the current situation illustrated in Figure 1, the PRG contemplates the removal of the road intersection located between the two roundabouts. The new system provides for the addition of a third roundabout, as shown in Figure 2 that substitutes the connection road in question.

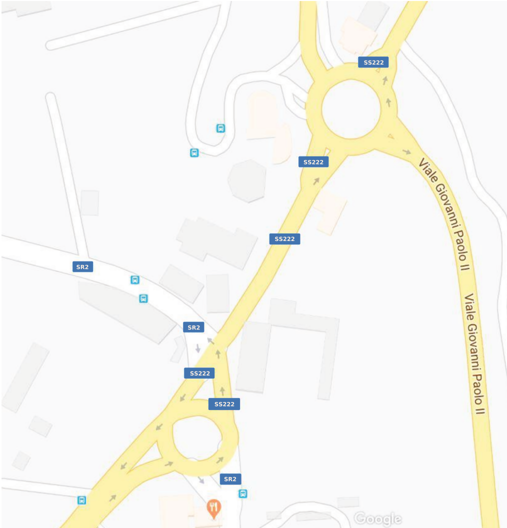


Figure 1. Actual system configuration

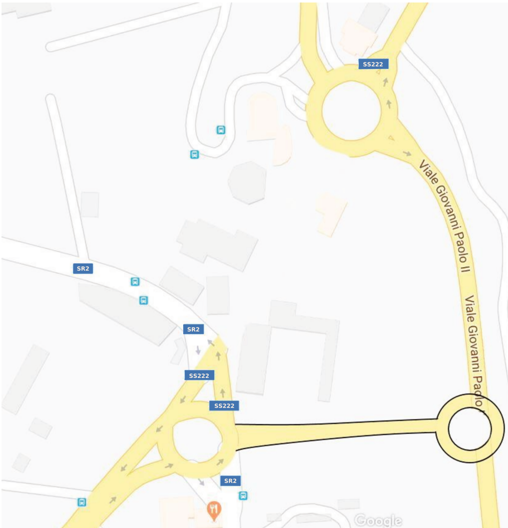


Figure 2. PRG system configuration

The illustrations above show the actual North Siena system and the one foreseen by the PRG.

The details of the modeling procedure of the two systems are not described in this paper due to limited space, but rather, a graphical mode will be used to explain the various component modeling steps in the individual traffic systems. In this way implementations of items from the object library on which our modeling technique is based will be illustrated for each intersection. The objects from the library as well as the procedure for generating the *Model.dat* file that contains the traffic system modeling data are described in some of our previous works [1–3].

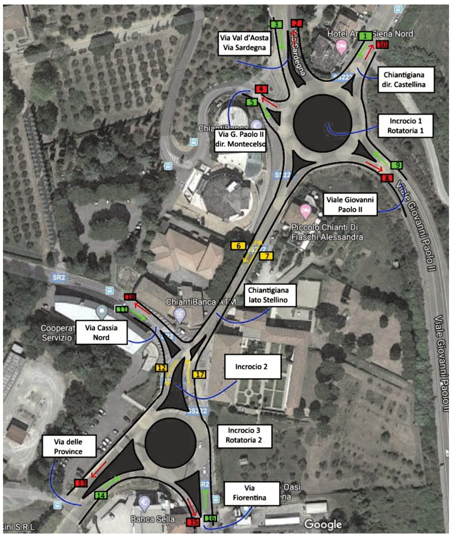


Figure 3. Actual North Siena system with associated numbers and roads

2. Modeling

The North Siena system structure and the alternative one will be described in this paragraph.

The original model is formed by three intersections, two of them are roundabouts. The intersections in the system are:

- **Crossroad 1**: corresponds to the northernmost roundabout (identified as Roundabout 1);
- **Crossroad 2**: corresponds to the intersection that joins the two roundabouts, it conveys vehicles coming from Roundabout 1 from the north, those coming from Roundabout 2 from the south, vehicles entering and exiting Via Cassia Nord from the west;
- **Crossroad 3**: corresponds to the southernmost roundabout (identified as Roundabout 2).

Figure 3 shoes how Roundabout 1 involves: Viale Giovanni Paolo II (formerly Strada Fiume), State Road N. 222 called Chiantigiana (towards Castellina in Chianti), Via Valle d'Aosta / Via Sardegna, Viale Giovanni Paolo II (towards Montecelso) and State Road N. 222 Chiantigiana (Stellino side).

Roundabout 2 involves the following roads: Via Fiorentina, Via delle Province, Via Cassia Nord and State Road N. 222 Chiantigiana (Stellino side) which connects the two roundabouts.

In Figure 3 streets are numbered in addition to the street names and roundabout identifiers. The numbers associated with the streets are the unique identifiers of the streets in the system and are used in the *Model.dat* file that describes the queue network model corresponding to the vehicular traffic system. The *Model.dat* file is a text file that contains a list of the system components and how these elements are connected with each other. The technique with which the *Model.dat* file of a given traffic system is generated is described in some of our previous works [1, 2], also for the two specific systems which will be compared in this work. It is also possible to notice in the figure that the directions of the two-way streets are considered separately and with different numbers. Each direction of travel has an associated color:

- **Red**: all the roads out of the system, i.e. those that lead vehicles outside the traffic system;
- **Green**: all the roads entering the system, i.e., those that lead vehicles to enter the traffic system;
- **Yellow**: all internal routes, which allow vehicles to move within the system.

This formalism is valid also for the other model.
In conclusion, the system has eighteen roads:

- 7 entering (1, 3, 5, 9, 11, 14, 16)
- 7 exiting (2, 4, 8, 10, 13, 15, 18)
- 4 internal (6, 7, 12, 17)

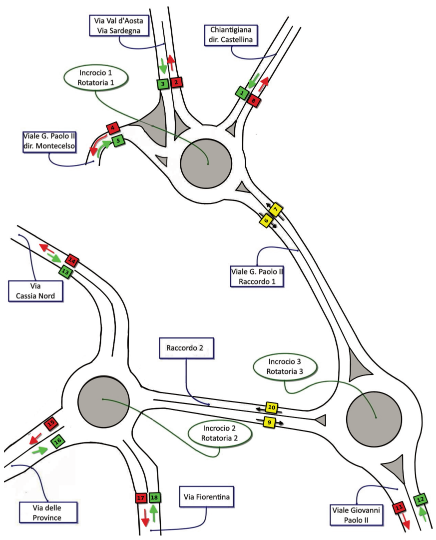


Figure 4. PRG North Siena system with associated numbers and roads

Instead, here it will be shown how the alternative three-roundabout model can be represented through the municipal project. The three-roundabout project was designed with the aim of significantly reducing congestion and streamlining traffic. As we will see, the system consists of three intersections / roundabouts, with two other connecting roads to join the new roundabout to the two already existing ones, as shown in Figure 4. The figure has been slightly modified compared to that created in the previous works. In fact, now Roundabout 2 is more similar to

the model created in the PRG of the Municipality of Siena and some streets have been renamed.
Let us see the composition:

- **Crossroad 1**: corresponds to the northernmost roundabout (identified as Roundabout 1);
- **Crossroad 2**: corresponds to the southernmost roundabout (identified as Roundabout 2);
- **Crossroad 3**: corresponds to the new roundabout located along Viale Giovanni Paolo II, slightly to the east of Roundabout 2 (identified as Roundabout 3);
- **Junction 1**: corresponds to the portion of Viale Giovanni Paolo II that connects Roundabout 1 to Roundabout 3, allowing them to be connected;
- **Junction 2**: corresponds to the new road built to join Roundabout 2 to the new Roundabout 3.

In addition to the above, there are further affected roads that allow entry, transit and exit from the system. As for Roundabout 1, State Road N. 222 Chiantigiana (towards Castellina in Chianti), Via Valle d'Aosta and Viale Giovanni Paolo II (towards Montecelso) are involved. Roundabout 2 involves Via Cassia Nord, Via delle Province and Via Fiorentina. Roundabout 3 instead is involved only from Viale Giovanni Paolo II to the south.
In conclusion, also this system has eighteen roads:

- 7 entering (1, 3, 5, 12, 13, 16, 18);
- 7 exiting (2, 4, 8, 11, 14, 15, 17);
- 4 internal (6, 7, 9, 10).

3. Crossroads

The following paragraph will allow us to better understand the composition of each single intersection present within the current and alternative North Siena systems. Each crossroad will be considered autonomously and will be composed of elements called sections. The latter will be mainly of three types:

- **Entry Sections**: these sections are marked in green, they represent the lanes to enter the crossroad studied, they can be considered as traffic channeling lanes;
- **Exit Sections**: these sections are marked in red, they represent the exit lanes from the crossroad analyzed, letting vehicles exit the affected area;
- **Internal Sections**: these sections are marked in yellow at intersections and with black arrows in roundabouts; they are represented by arches of arrows (for roundabouts) and yellow squares (for intersections) and correspond to internal areas of the crossroads where the transit of vehicles is mandatory following a crossing path.

Each intersection will present its entrance and exit sections, its internal sections and the possible crossing paths taken by passing vehicles. Each section will have its own numeric ID which will then be used to identify the section within the *Model.dat file.*

3.1. Two-roundabout Model

In Figure 5 we can see Roundabout 1 which is made up of a total of 10 in/out sections, 5 at the entrance (marked in green) and 5 at the exit (marked in red).

Let us analyze the entrance sections of Roundabout 1:

- **Entry Section 1**: the entry point in the roundabout for vehicles coming from State Road N. 222 Chiantigiana (towards Castellina in Chianti);
- **Entry Section 2**: the entry point into the roundabout for vehicles coming from Via Valle d'Aosta;
- **Entry Section 3**: the entry point into the roundabout for vehicles coming from Viale Giovanni Paolo II (towards Montecelso);
- **Entry Section 4**: the entry point in the roundabout for vehicles coming from State Road N. 222 Chiantigiana (Stellino side);
- **Entry Section 5**: the entry point into the roundabout for vehicles coming from Viale Giovanni Paolo II.

The sections leaving the roundabout are instead listed as follows:

- **Exit Section 1**: the exit point from the roundabout which enters Via Sardegna (formerly Valle d'Aosta);
- **Exit Section 2**: the exit point from the roundabout which enters Viale Giovanni Paolo II (towards Montecelso);
- **Exit Section 3**: the exit point from the roundabout which joins State Road N. 222 Chiantigiana (Stellino side);
- **Exit Section 4**: the exit point from the roundabout which enters Viale Giovanni Paolo II;
- **Exit Section 5**: the exit point from the roundabout which joins State Road N. 222 Chiantigiana (towards Castellina in Chianti).

Figure 5 also illustrates the twenty internal sections inside the roundabout. In the modeling it was established that the internal sections near the entrance and exit sections could contain only one vehicle, while those inside the roundabout could contain many. This factor is repeated in all future modeling of intersections.

Figure 6 shows the entrance and exit sections of Roundabout 2, located south of the system. The entrance sections are as follows:

- **Entry Section 1**: the entry point into the roundabout for vehicles coming from the Via Cassia Nord branch;
- **Entry Section 2**: the entry point into the roundabout for vehicles coming from Via delle Province;
- **Entry Section 3**: the entry point into the roundabout for vehicles coming from the internal lane of Via Fiorentina;
- **Entry Section 4**: the entry point into the roundabout for vehicles coming from the external lane of Via Fiorentina.

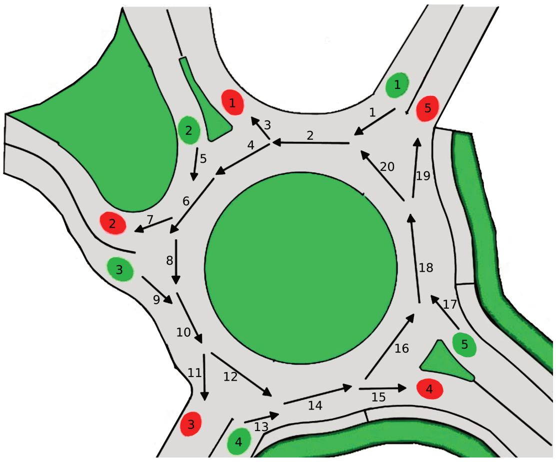


Figure 5. Roundabout 1 with entry, exit and internal sections

The exit sections are:

- **Exit Section 1**: the exit point from the roundabout which enters Via delle Province;
- **Exit Section 2**: the exit point from the roundabout which joins Via Fiorentina;
- **Exit Section 3**: the exit point from the roundabout for vehicles which enters the road 17 in the model, towards Intersection 2, directed to Via Cassia Nord;
- **Exit Section 4**: the exit point from the roundabout for vehicles flows towards the road 7 in the model, i.e., State Road N. 222 Chiantigiana (Stellino side), directed to Roundabout 1.

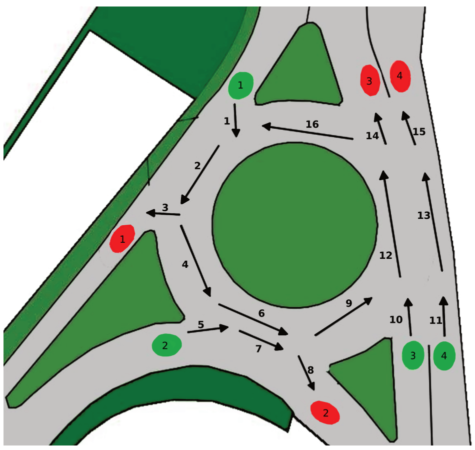


Figure 6. Roundabout 2 with entry, exit and internal sections

Figure 6 also illustrates the structure of the sixteen internal sections at the intersection. In this case, the identification of the internal sections at the intersection was made more accurately by improving the description of the vehicular flows crossing the intersection. In particular, an internal section was added between the entrance from Via delle Province and the direct exit towards Via Fiorentina. This section (No. 7) was inserted because it was found that the space was sufficient to contain two parallel lanes that would allow an additional flow to the exit towards Via Fiorentina.
Let us now pass to the analysis of Crossroad 2, located between the two roundabouts of the current North Siena system and shown in Figure 7.

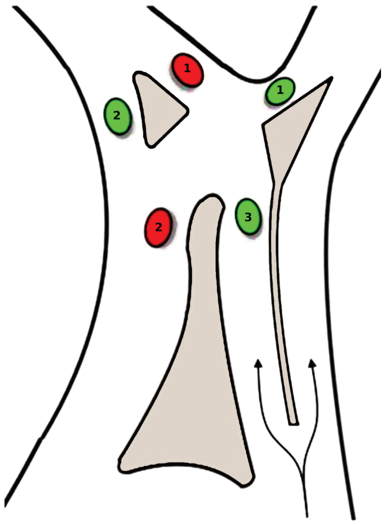


Figure 7. Crossroad 2 with entry and exit sections

The model of Crossroad 2, as can be seen in Figure 7, has 5 In/Out sections, 3 entries (in green) and 2 exits (in red). Let us analyze the entry sections:

- **Entry Section 1**: the entry point at the intersection for vehicles coming from State Road N. 222 Chiantigiana (Stellino side) and heading south or towards Via Cassia Nord;
- **Entry Section 2**: the entry point at the intersection for vehicles coming from Via Cassia North and heading south;
- **Entry Section 3**: the entry point at the intersection for vehicles coming from Roundabout 2 and heading towards Via Cassia Nord;

The exit sections are listed as:

- **Exit Section 1**: the exit point from the intersection that enters Via Cassia Nord;
- **Exit Section 2**: the exit point from the intersection that enters road 12 in the model, towards Roundabout 2.

The graphical representations of the crossing paths that vehicles can take at the intersection are shown below. There are four possible crossing paths. In this model there are three internal sections and they are graphically identified by yellow squares.

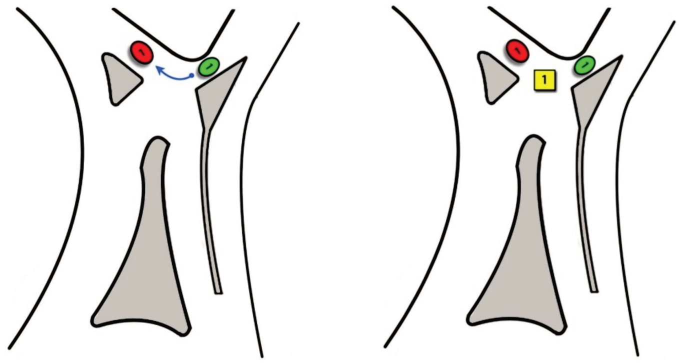


Figure 8. Vehicle going from Entrance 1 to Exit 1 with trajectory and internal sections crossed

The first analyzed case is the one which goes from the Entrance 1 to Intersection (coming from Chiantigiana on the Stellino side) towards Exit 1 (Via Cassia Nord). As can be seen from Figure 8, the internal section concerned is 1.

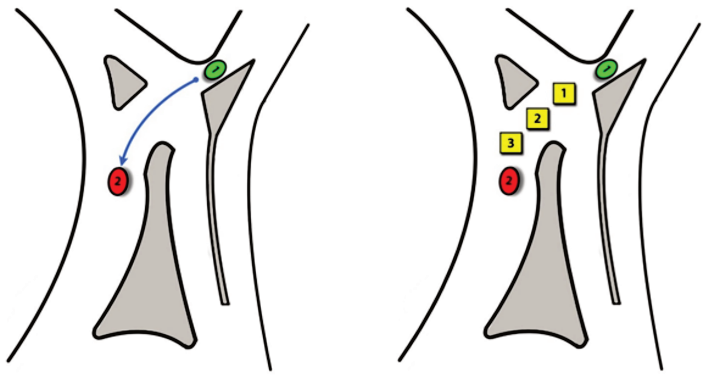


Figure 9. Vehicle going from Entrance 1 to Exit 2 with trajectory and internal sections crossed

The second case analyzes the crossing path by which the vehicle enters the intersection from Entrance 1 (Chiantigiana on the Stellino side) and heads to Exit 2, towards Roundabout 2. Figure 9 shows that in this case the vehicle crosses all the three interior sections.

The third crossing path is the one that leads vehicles from Entrance 2, entering the flow from via Cassia Nord, to Exit 2, towards Roundabout 2. In Figure 10 we can also see how the vehicle transits in the internal Section 3 only.

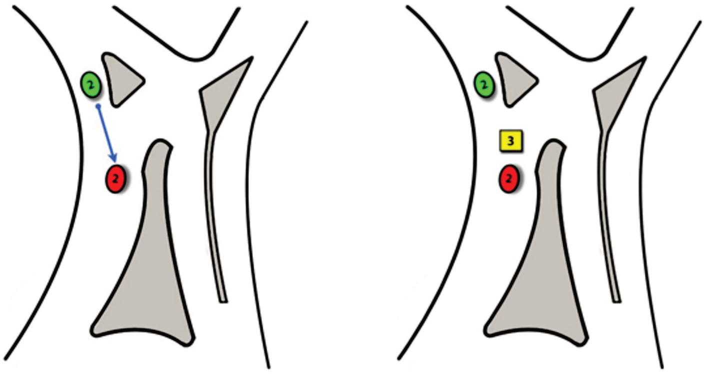


Figure 10. Vehicle going from Entrance 2 to Exit 2
with trajectory and internal sections crossed

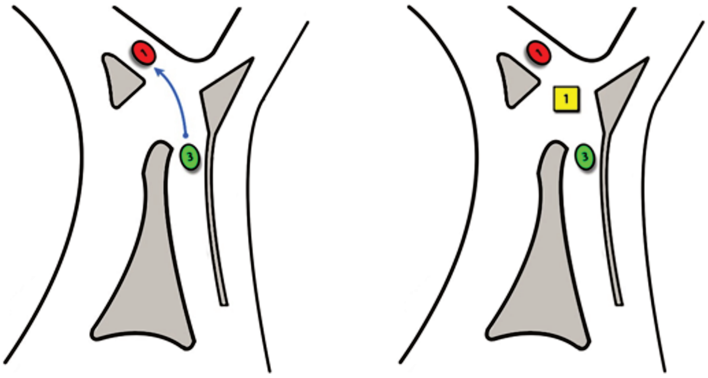


Figure 11. Vehicle going from Entrance 3 to Exit 1
with trajectory and internal sections crossed

The fourth crossing path is the one that allows vehicles to go from Entrance 3, the flow coming from Roundabout 2, to Exit 1, towards Via Cassia Nord. Figure 11 shows how vehicles must cross the internal Section 1 to take the mentioned road section.

3.2. Three-roundabout Model

In Figure 12 it is possible to see how Roundabout 1, i.e., the one located further north in the new system model in the PRG of the Municipality of Siena, has a total of 8 In/Out sections: 4 Input sections and 4 Output sections
Let us analyze the entry sections:

- **Entry Section 1**: the entry point in the roundabout for vehicles coming from State Road N. 222 Chiantigiana (towards Castellina in Chianti);
- **Entry Section 2**: the entry point into the roundabout for vehicles coming from Via Valle d'Aosta;
- **Entry Section 3**: the entry point into the roundabout for vehicles coming from Viale Giovanni Paolo II (towards Montecelso);

- **Entry Section 4**: the entry point into the roundabout for vehicles coming from Viale Giovanni Paolo II (connection with Roundabout 3).

Instead, the below exit sections are analyzed:

- **Exit Section 1**: the exit point from the roundabout which enters Via Sardegna;
- **Exit Section 2**: the exit point from the roundabout which enters Viale Giovanni Paolo II (towards Montecelso);
- **Exit Section 3**: the exit point from the roundabout which enters Viale Giovanni Paolo II (connection with Roundabout 3);
- **Exit Section 4**: the exit point from the roundabout which joins State Road N. 222 Chiantigiana towards Castellina in Chianti.

The figure represents the model of Roundabout 1, which also shows the sixteen internal sections.

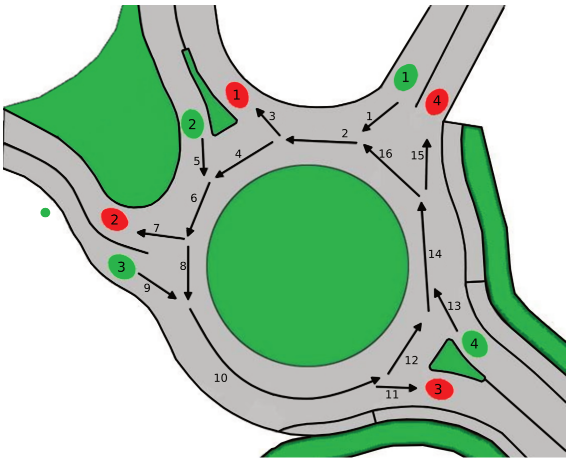


Figure 12. Roundabout 1 with entry, internal and exit sections

In Figure 13, the entrance and exit sections of Roundabout 2 of the three-roundabout model are drawn. In this modeling, the area between Entrance 3 and Exit 3 has been modified compared to a study previously carried out [2]. This new structure is closer to the description of the project that is exposed in the PRG of the Municipality of Siena that we have as a reference.

Let us analyze the entrance sections of the roundabout:

- **Entry Section 1**: the entry point into the roundabout for vehicles coming from Via Cassia Nord;
- **Entry Section 2**: the entry point into the roundabout for vehicles coming from Via delle Province;
- **Entry Section 3**: the entry point into the roundabout for vehicles coming from Via Fiorentina;
- **Entry Section 4**: the entry point into the roundabout for vehicles coming from the junction with Roundabout 3.

Here are the outgoing sections.

- **Exit Section 1**: the exit point from the roundabout which enters Via delle Province;
- **Exit Section 2**: the exit point from the roundabout which joins Via Fiorentina;
- **Exit Section 3**: the exit point from the roundabout that joins the junction towards Roundabout 3;
- **Exit Section 4**: the exit point from the roundabout which enters Via Cassia Nord.

The figure also shows the sixteen internal sections inside Roundabout 2.

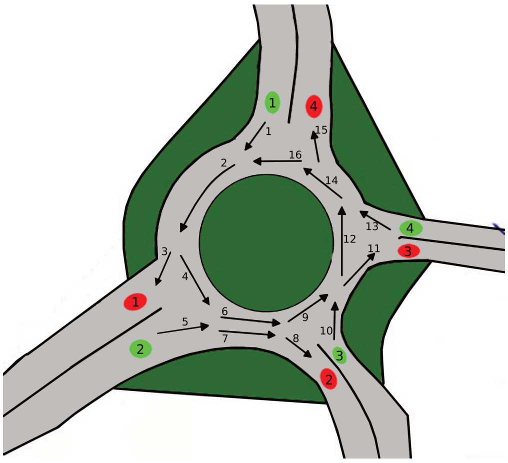


Figure 13. Roundabout 2 with entry, internal and exit sections

Roundabout 3 represents the main modification envisaged by the PRG of the Municipality of Siena. Figure 14 shows the entrance and exit sections of the roundabout.

Analyzing the entry sections, one can see:

- **Entry Section 1**: the entry point into the roundabout for vehicles coming from Viale Giovanni Paolo II (connection with Roundabout 1);
- **Entry Section 2**: the entry point into the roundabout for vehicles coming from the junction with Roundabout 2;
- **Entry Section 3**: the entry point into the roundabout for vehicles coming from Viale Giovanni Paolo II.

As for the exit sections instead:

- **Exit Section 1**: the exit point from the roundabout which joins the junction with Roundabout 2;
- **Exit Section 2**: the exit point from the roundabout which enters Viale Giovanni Paolo II;

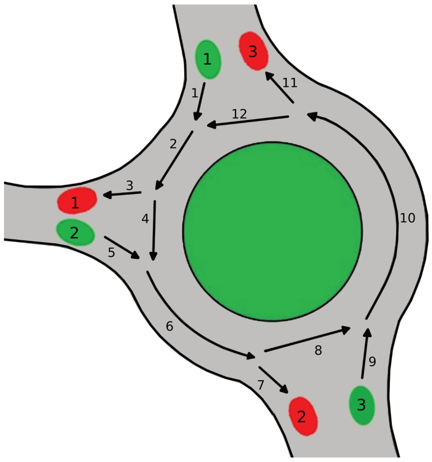


Figure 14. Roundabout 3 with entry, internal and exit sections.

- **Exit Section 3**: the exit point from the roundabout which enters Viale Giovanni Paolo II (connection with Roundabout 1).

The figure also describes how the twelve internal sections of the new roundabout would be, computed from the interactive map of the new PRG.

4. Systems simulation and results visualization

In the previous works [1–3] we have shown that the modeling phase of the traffic system ends with the production of the Model.dat file, which is a text file that contains data relating to the components of the system model. In this case, two different types of Model.dat files relating to the structure of the two alternative traffic systems are obtained: the current traffic system and the three roundabout traffic system envisaged by the PRG. The Model.dat file contains the list of model components with their parameters. This data includes data on vehicular traffic flows that were detected by the municipal administration at the entry and exit points of the intersections. The tables of vehicle traffic data relating to the North Siena system are shown in [2] for the current system and in [1] or the system envisaged by the PRG.

In our previous research work, using the QNAP2 programming context [4], we built a procedure which, when executed, reads the data contained in the Model.dat file and generates the corresponding traffic system simulator. In this way, starting from the Model.dat file relating to each of the two models of alternative traffic systems, considered in one of the three time bands identified by the data on vehicular traffic, we built a simulator of the current system and a simulator of the three-roundabout system foreseen by the PRG for each of the three considered time bands. We then performed a simulation of the two traffic systems in the three time bands identified from the traffic data tables that were provided by the Municipal Administration. We basically built six simulators. The time slots considered were the following:

- **Morning** 7:30 - 9:00
- **Afternoon** 12.00 - 13.30
- **Evening** 17:50 - 19:20

The performed simulations allowed us to trace the evolution of vehicle flows within the two systems in each of the three time slots. In this way we were able to record the levels of traffic congestion that occurred at the individual points within the system. To automatically perform the analysis of congestion events occurring during the simulation of a system, we built an application that would read the simulation tracing file and graphically display the state of traffic congestion at points inside the system. In the following paragraph the components of application this for the graphic display of the simulation tracking will be briefly described and then the congestion levels that were detected by simulations of the current two roundabout system and the three roundabout systems provided by the PRG will be compared in each of the three time slots: morning, afternoon and evening.

4.1. Composition of application

The application was developed in Visual Basic and consists of two main interfaces, as shown below:

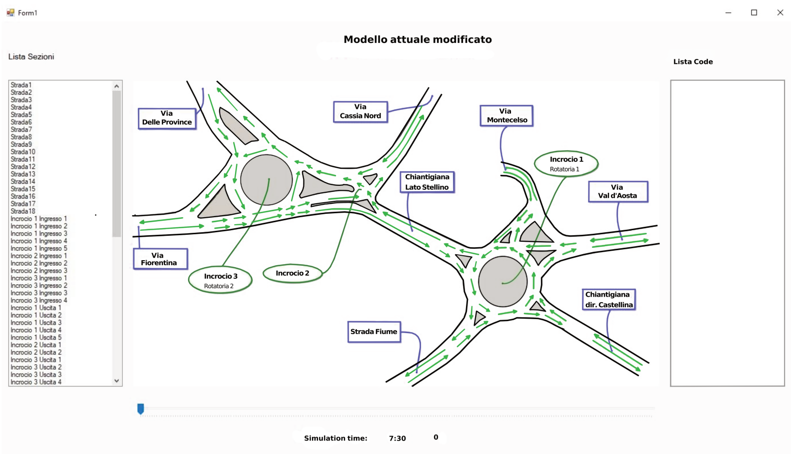


Figure 15. Example of Form 1

As can be seen in Figure 15, Form 1 represents the map of the simulated traffic system. In the specific case shown in Figure 15 it is the current two roundabout system. The map shows all the points inside the system with the vehicular flow. These internal points are indicated with arrow arcs and each of these corresponds to an element that was used in the modeling of the system. The list of streets, the entrance, exit and internal sections of all the intersections and roundabouts that are present in the system are shown on the left. On the right, there is a list of sections that present vehicle queues at a specific time of execution of the simulation. Clicking on one of the sections found in this list opens the form,

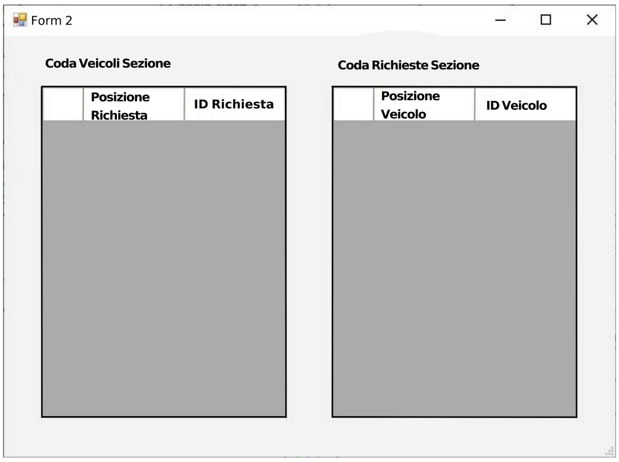


Figure 16. Example of Form 2

which is shown in Figure 16. This second window has the task of showing the queue of vehicles in the section that has been selected and the corresponding queue of requests to access that section, according to the operating modes of the simulator. The example in the figure below better exemplifies what has been said.

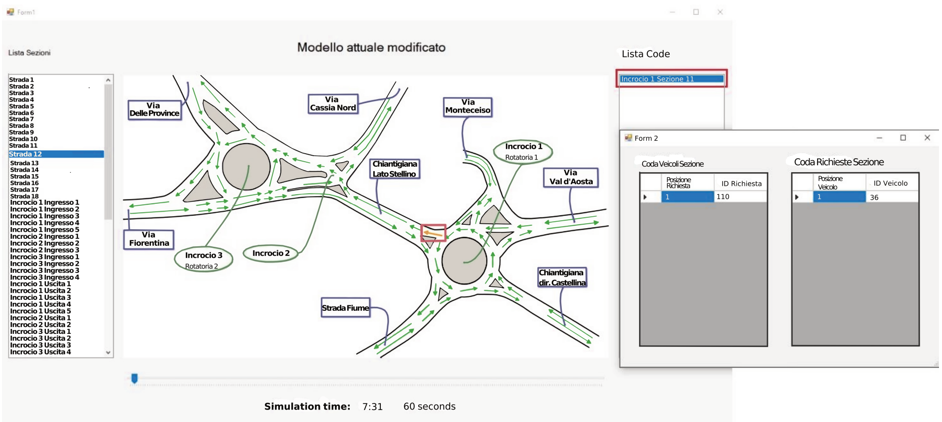


Figure 17. Queue example in Form 1 and Form 2

The example in Figure 17 shows how a queue of vehicles and a queue of requests appear in Section 11 of Intersection 1 in the first minute of the simulation. This mild congestion event at an exit point from Roundabout 1 is highlighted in the map by flow arrows corresponding to the point inside the system where congestion has occurred, which is colored in orange. In the case of heavy congestion events, the color of the flow arrows of the corresponding points on the map becomes red. The operation of the application is based on reading the data contained in a text file that is generated and written by some procedures that are defined within the code of the simulation program. At the end of the simulation, the graphic application reads the aforementioned file line by line in order to extrapolate the relevant information in the time interval that has been established by the user. Let us now explain how forms work and how they receive the data to display.

- **Form 1**: In the first form, the map shown is taken as the input from a certain path, while the arrows of the flows inside it are images created individually (for each of the three possible colors) which indicate the intensity of traffic in the relative section, green - if there are no requests for access to the section, orange - when the number of requests is equal to or greater than one of the maximum numbers of vehicles acceptable in the section, and red, if the requests exceed at least two of the maximum numbers of vehicles acceptable in the section. The list of flows is contained in an array, and each flow is associated with the index of its position within it. In this way, by scrolling the text file of the results, it will be possible to act on certain flows based on the corresponding code. Below the model there is a scroll bar that allows choosing the desired time interval, shown in both seconds and hours through the appropriate labels. When the bar is moved, the results file will be read again and the data will vary accordingly.
- **Form 2**: When a section in the flow lists is clicked, the second form will appear. The application takes as parameters the identifier of the selected section, the array of vehicles already inside the section, at this point the file is read again to find the list of vehicle identifiers contained in these queues which will be shown on the corresponding lists, the first for vehicles in the section, the second for section requests.

4.2. Morning comparison

The analysis of vehicle queuing events in the two traffic systems in the morning time slot will be shown now. The following tables show all the queues that occur every 300 seconds. The tables show the time instants during the simulation on the vertical axis, while the queues of vehicles that are present in the various points of the system on the horizontal axis. For the sake of clarity, we have chosen the sequence of instants of detection of the system status which are shown in the following tables, corresponding to an instant of observation every 5 minutes on the real system. The simulations performed also involved sequences of much more frequent observation instants.

Each box corresponding to a queue will contain the following data : the roundabout (or intersection) identifier, the section identifier and the number of vehicles in the queue. As regards the second field, it is pointed out that the acronym S is equivalent to the Internal Section, U to the Exit Section, E to the Entry Section. Finally, the total number of vehicles queued in that instant of time is shown in the last column.

The boxes with the highest number of vehicles within the section will also be shown in yellow, while the interval in which there are more vehicles in the queue will be shown in green.

Three-roundabout system – Morning								
Time	Q1	Q2	Q3	Q4	Q5	Q6	Q7	V.Q.
300	R1S13:2	R2U3:2						4
600	R1S5:2	R2S1:2	R2S8:2					6
900	R1S11:2	R1S15:2	R3S11:2	R3S9:2	R3S7:2	R3U1:2		12
1200	R3S9:2	R2S6:2	R2U3:2	R1S11:2	**R1E2:8**			**16**
1500	R1S15:2	R1U3:2	R2S8:2	R2U3:2	R3S3:2			10
1800	R3U2:2	R3S5:3	R2S11:2	R2U3:2	R1S5:2	R1S15:2		13
2100	R1S14:3	R1S11:2	R1U3:2	R2U4:2	R2S11:3	R3S1:2		12
2400	R2S13:2	R2S1:2	R1U4:2					6
2700	R1S11:2	R1U4:2	R1S1:2	R2S6:2	R2S10:2			10
3000	R1S1:2	R3U3:2	R3S7:2	R3S9:2				8
3300	R3S7:2	R3U1:2	R2U3:2	R2S3:2	R1S13:2	R1U4:2	R1S1:2	14
3600	R1S11:2	R1U3:2	R2S3:2	R2S8:2	R2S11:2			10
3900	R1U3:2	R1S1:2	R1S15:2	R1S5:2	R2S10:2	R3S11:2		12
4200	R1S11:2	R1S15:2	R1U4:2	R1S5:2	R2S10:2	R3S1:2	R3U2:2	14
4500	R1S13:2	R1S15:2	R3U3:2	R3S1:2	R3S5:2			10
4800	R1S1:2	R2S10:2	R3S1:2	R3S3:2	R3U3:2			10

The following table shows data relating to the morning slot of the three roundabout system.

The table below is for the current two roundabout model in the morning time slot. In this case the numbering of the intersections goes from northernmost to southernmost.

Comparing the two tables reported here it can be seen that in this time slot there are fewer queues in the current system than in the three-roundabout system provided by the PRG. Even the total number of queued vehicles according to the observation instant is almost always lower in the current system than the corresponding values in the system provided for by the PRG. A figure that can be calculated is the sum of all the vehicles present in the queues in the morning time slot. In the three roundabout system, the total queued vehicles are 167, while there are 117 of them in the two-roundabout system.

As can be seen in the last column of the tables, the maximum number of vehicles in the queue in the detected instants of time is 16 vehicles in the queue throughout the system in both cases. In the three roundabout system, the peak is reached at 1200 seconds and then in the early morning, while in the two roundabout system the peak is reached at 4800 seconds.

A final detail that can be noticed is the presence of important queues within the two systems. In the case of the PRG system, there is only one queue, in the early morning, which causes slowdowns in the section marked in yellow. On the other hand, in the two roundabout model we notice many more points

Two-roundabout system – Morning								
Time	Q1	Q2	Q3	Q4	Q5	Q6	Q7	V.Q.
300	I1S19:2	I2S1:2						4
600	I1S5:2	I1S17:2						4
900	I3S1:2	I2S3:2						4
1200	**I1E2:8**							8
1500	**I1E4:6**							6
1800	I1S5:2	I2E2:2						4
2100	**I1E4:8**	I2S3:2						10
2400	**I1E4:6**	I2S1:2	I2S3:2					10
2700	I1S1:2	I2E1:2						4
3000	I1S1:2	I1S13:2	I3S15:3	I2E1:2	I2S2:2			11
3300	I1S1:2	I3S1:2						4
3600	I1S15:2	I1S19:2	I3S1:2	I3S3:2	I2E1:2			10
3900	I1S1:2	I1S5:2	I1S15:2					6
4200	I1S5:2	I1S11:2	I1S17:2	I3S3:2	I2E1:2			10
4500	I1S17:2	I3S1:2	I3S3:2					6
4800	I1S1:2	I1S13:3	I1S17:2	**I1E4:7**	I2E1:2			**16**

where vehicles are in important queues, especially concentrated on Intersection 1, which is the roundabout that is further north in the current system, especially at Entrance Section 4, where they often experience traffic jams.

4.3. Afternoon comparison

We repeat the scheme seen in the morning comparison, showing first the behavior of the three-roundabout system, then that of the current system and finally making the necessary considerations between the two systems.

In the afternoon time slot, the total number of queues detected in the simulation is greater for the three roundabout model which is foreseen by the PRG than for the current two roundabout model.

As for the total number of queued vehicles detected in the afternoon time slot, it is pointed out that it is 158 in the three roundabout system, while in the current two roundabout system it is 88.

As for the analysis of the simulation in the sequence of the time instants set, in this case, there are more vehicles queuing in the two roundabout model, at the instant 3900 to be precise, with 17 vehicles in the whole system. The three roundabout system, on the other hand, reaches a maximum of 14 queued vehicles in total, at the instants of 900 sec and 3600 sec.

Finally, the absence of important queues throughout the afternoon time slot for both the compared vehicle traffic models is indicated.

Three-roundabout system - Afternoon								
Time	Q1	Q2	Q3	Q4	Q5	Q6	Q7	V.Q.
300	R1S11:2	R115:2	R1U4:2	R2S13:3				9
600	R1U4:2	R3S3:2						4
900	R3S3:2	R3U1:2	R3U2:2	R1U3:2	R1E4:4	R1U4:2		**14**
1200	R1S1:2	R1S13:2	R2S11:2					6
1500	R2S6:2	R2S14:2	R3S1:2	R2S11:2	R1S11:2	R1U4:2		12
1800	R1S11:2	R1S15:2	R2S15:2	R2U4:2	R3S1:2	R3U1:2		12
2100	R3S3:2	R3U1:2	R2U2:2	R2U4:2	R2S10:2	R2S13:2		12
2400	R3S1:2	R2S3:2	R1S13:2	R1S15:2	R1U4:2			10
2700	R1S11:2	R1U4:2	R2S13:3	R3S1:2				9
3000	R3U3:2	R3S1:2	R3S7:2	R2S13:2	R1U4:2			10
3300	R2U3:2	R3S1:2	R3S9:2	R1S15:2	R1S7:2			10
3600	R1U3:2	R1U4:2	R1S5:2	R1S15:2	R2U4:2	R2S13:2	R3S7:2	**14**
3900	R2S13:3	R2U2:2	R1S15:3					8
4200	R1S1:2	R2S1:2	R3U3:2	R3S1:2				8
4500	R3S1:2	R2U3:2	R1S13:3					7
4800	R1S5:2	R1S15:2	R2U2:2	R2S13:3	R3S5:2	R3U3:2		13

Two-roundabout system - Afternoon								
Time	Coda 1	Coda 2	Coda 3	Coda 4	Coda 5	Coda 6	Coda 7	V.Q.
300	I1S15:2	I2S1:2	I2E2:2					6
600	I2E2:2							2
900	—							0
1200	I1S1:2	I2E2:2	I2S1:3					7
1500	I1S15:3	I3S3:2	I2E1:2					7
1800	I1S13:2	I3S3:2	I2E1:2					7
2100	I1S11:2							2
2400	I3S3:2	I2S1:3						5
2700	I3S3:2							2
3000	I2E1:2							2
3300	I3S3:2							2
3600	I1S5:2	I1S19:2	I3S1:2	I2E1:2				8
3900	I1S13:3	I1S15:2	I1S19:3	I3S3:2	I2E2:2	I2S1:3	I2S3:2	**17**
4200	I1S1:2	I1S13:3	I3S1:2	I2E2:2				9
4500	I1S17:2	I3S3:2	I2E3:2					6
4800	I1S5:2	I1S15:2	I1S17:2					6

4.4. Evening comparison

In the two preceding time bands the simulation tracking tells us that the traffic congestion levels are distributed in a different way in the two compared models. However, both models are characterized by low levels of congestion with queues of vehicles occurring uniformly in the two time bands with only some isolated events in time with a maximum number of vehicles queued not exceeding 8.

The evening time slot is instead characterized by a much more congested trend in internal vehicle flows than in the two previous time slots for both models. Also in this case, congestion events are distributed differently in the two traffic models. For the three roundabout system envisaged by the PRG, the situation in the observation instants is shown in the following table:

The first thing to be noted is the presence of new values within the two tables above. In fact, compared to the previous time slots, these tables show a queue relating to some roads of the two alternative models. Road 18 appears in the queuing table of the model relating to the three roundabout system envisaged by the PRG, which corresponds to Via Fiorentina in the stretch of entry to Roundabout 2. Two roads appear in the queuing table of the model relating to the current system: Road 7 which is State Road N. 222 via Chiantigiana on the Stellino side in the section that carries the vehicular flow from Roundabout 2 towards Roundabout 1 and Road 16 which in this model corresponds to via Fiorentina in the stretch of entrance to Roundabout 2. The boxes corresponding to these queues are colored in red when the road has exceeded its saturation level i.e. the maximum number of vehicles which it can contain inside and are in orange when they exceed 93% of the saturation level. The data has been included in the tables as it illustrates the actual queuing and congestion events within the system that did not occur in the models relating to the two time slots of the morning and afternoon. The number of vehicles that appear in the queues inside the streets has not been included in the final count of vehicles in the queue in the last column of the table.

Returning to the considerations for the other two bands, an incredible worsening of the traffic situation in the current two roundabout system is noted, despite the fact that the situation of the distribution of queues between the various time bands is almost similar.

As for the total number of vehicles creating queues, it can be seen how the current model exceeds the other one by almost 200 vehicles, with 614 vehicles compared to 416 for the three roundabout model.

The spike in queuing is also drastically negative for the two-roundabout system. In fact, 56 vehicles blocked at 1800 and 3300 seconds can be eventually observed, compared to 41 in of the model with three roundabouts, which however, appear in the instant of 1500 seconds only.

The comparison of the evening is concluded with the most particular and interesting data that affect the global evaluation of both systems, i.e., the critical

Three-roundabout system - Evening													
Time	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	V. Q.
300	R1S 5:2	R1U 3:2	R1S 11:2	R1S 13:2	R2U 1:2	R2S 11:2	R2S 13:2	R3S 1:2					16
600	R3U 2:2	R3S 1:2	R3S 5:3	R3S 11:2	R2U 3:2	R1S 11:2	R1S 13:2						15
900	R1S 1:2	**R1E 4:5**	R2S 1:2	R2S 3:2	R2S 8:2	R2S 10:2	**R3E 2:7**	R3S 5:3	R3S 11:2	R3U 3:2			29
1200	R3U 2:2	R3S 7:2	R2S 1:2	R2S 13:2	R2S 11:2	R2S 15:2	R1E 4:4	R1S 1:2	R1S 15:2				20
1500	R1S 5:2	R1S 15:2	R1U 3:2	R1E 4:4	R2S 3:2	R2S 5:2	**R2E 3:11**	R2S 11:2	R2U 3:2	**R3E 2:7**	R3S 5:3	R3S 11:2	**41**
1800	R3S 11:2	**R3E 2:7**	**R2E 3:11**	R2S 10:3	R2S 5:2	R1S 5:2	R1S 15:3	R1E 4:-4	R1U 3:2				36
2100	R1S 15:2	**R2E 3:11**	R2S 10:3	R2S 15:2	R2U 1:2	**R3E 2:7**	R3S 11:3	**Ro1 8:67**					30
2400	R3U 2:2	R3U 3:2	R3S 5:2	R2S 8:2	R2S 10:3	**R2E 3:11**	**Ro1 8:69**	R1S 1:2	R1S1 5:2	R1E 4:4			30
2700	R1S1 5:2	R1U 4:2	R1E 4:4	R3S 11:2	R3U 1:2	R2S 15:2	R2S 11:2	**R2E 3:11**	R2U 4:2	**Ro1 8:99**			29
3000	R2U 4:2	R2S 1:2	**R2E3 :11**	**Ro18 :127**	R3S 5:2	R3S 11:2	R3S 7:2	R1S 13:2	R1S 15:2	R1S 5:2			27
3300	R1S 5:2	R1S 13:2	R1U 3:2	R2U 4:2	R2S 1:2	R2S 3:2	R2S 8:2	R2S 10:3	**R2E 3:11**	**Ro1 8:96**			28
3600	R1S 5:2	R1E 4:4	R3U 2:2	R2S 1:2	R2S 3:2	R2S 10:3	**R2E3 :11**	**Ro1 8:66**					26
3900	R1S 5:2	R1S 7:2	R2S 13:2	R2S 8:2	**R2E 3:12**	**Ro18 :105**							20
4200	R1S 5:2	R2S 11:2	R2U 3:2	**R2E3 :11**	**Ro18 :77**	**R3E 2:6**	R3S 5:3	R3S 11:2					28
4500	R1S1 5:2	R2S 13:2	**R2E 3:11**	**Ro18 :114**	R3U 3:2								17
4800	R1S 15:2	R1S 13:2	R1U 4:2	R2U 3:2	**R2E3 :11**	**Ro18 :76**	R3S 5:3	R3S 7:2					24

queues. In both models we note a considerable increase in this type of traffic congestion events, both in terms of quantity and the number of vehicles within the section concerned. It is evident, even upon immediate observation based on the colors of the boxes in the two tables, that the model relating to the current system is much more congested than the three-roundabout model that is provided for by the PRG. However, it must be noted that even for the three-roundabout model the congestion events inside the system, although they are distributed over a quite larger total surface area of this model compared to the current model,

Two-roundabout system - Evening														
Time	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	V. Q.
300	I1S 5:2	I1S 13:3	I1S 19:2	I3S 1:2	I3S 3-:2	I2E 1:2	I2S 1:3							16
600	I1S 7:2	I1S 13:3	I1S 15:2	I2E 1:3										10
900	I1S 1:2	I1S 11:2	I1S 17:2	I1S 19:2	**I1E 4:8**	I3S 5:2	I2E 1:2	I2S 2:2	I2S 3:3					25
1200	I1S 1:2	I1S 11:2	**I1E 4:8**	I2E 1:2	I2S 3:3	**Ro7 :31**								17
1500	I1S 5:2	I1S 13:3	**I1E 4:7**	**I3E 4:10**	I3S 3:2	I3S 11:2	I3S 5:2	**I3S1 3:14**	**I3S 15:8**	I2E 1:2	**Ro7 :31**			52
1800	I1S 5:2	I1S 13:3	**I1E 4:7**	**I3E 4:12**	I3S 5:2	**I3S 9:5**	I3S 11:3	**I3S1 3:12**	**I3S 15:8**	I2E 1:2	**Ro 7:32**			**56**
2100	I1S 13:3	**I1E 4:7**	**I3E 4:12**	I3S 9:4	**I3S1 3:13**	**I3S 15:7**	I2S 1:2	I2S 3:2	**Ro7 :33**	**R16 :72**				50
2400	I1S 1:2	**I1E 4:7**	**I3E 4:11**	**I3S1 3:12**	**I3S1 5:7**	I2E 1:2	I2S 2:2	I2E 2:2	**Ro7 :34**	**R16 :75**				45
2700	I1S 17:2	I1S 19:2	**I1E 4:7**	**I3E 4:12**	**I3S1 3:12**	**I3S1 5:5**	I2S 1:2	I2S 3:2	**Ro7 :34**	**R16 :69**				44
3000	I1S 5:2	I1S 17:2	I1S 19:2	**I1E 4:8**	**I3E 4:10**	I3S 1:2	I3S 11:3	**I3S1 3:13**	**I3S1 5:8**	I2S 1:2	I2S 3:2	**Ro7 :32**	**R16 :77**	54
3300	I1S 5:2	I1S 19:2	**I1E 4:8**	**I3E 4:11**	I3S1 1:3	**I3S1 3:13**	**I3S1 5:8**	I2E 1:2	I2S 2:2	I2S 3:3	I2E 3:2	**Ro7 :33**	**R16 :72**	**56**
3600	I1S 5:2	I1S 13:3	I1S 19:2	**I1E 4:7**	**I3E 4:11**	**I3S 15:6**	I2S 3:2	**Ro7 :34**						33
3900	I1S 4:2	I1S 11:2	I1S 13:3	**I1E 4:7**	**I3E 4:12**	**I3S 15:6**	I2S 1:2	**Ro7 :34**						34
4200	I1S 5:2	I1S 13:3	**I1E 4:7**	**I3E 4:12**	I3S 1:2	**I3S 15:5**	I2E 1:2	I2E 3:2	**Ro7 :34**					35
4500	I1S 19:2	**I1E 4:7**	**I3E 4:12**	I3S 11:3	**I3S1 3:13**	**I3S 15:8**	**Ro7 :32**							45
4800	I1S 19:2	**I1E 4:7**	**I3E 4:11**	I3S 11:3	**I3S1 3:11**	**I3S 15:8**	**Ro7 :33**							42

are not negligible. In fact, for this model, it is noted that Roundabout 2, at Entrance 3, is occupied from the second 1500 up to 4800 by about 11 vehicles. This congestion at the entry point of the roundabout is due to the fact that the entrance to Roundabout 2 from via Fiorentina is not sufficiently easy for the flow of the evening traffic so that the saturation of road 18 is determined upstream of this point of the system, which is shown in red in the table. This analysis highlights, in our opinion, the greatest criticality of the new model in the project that is foreseen by the PRG of the Municipal Administration of Siena.

If the same type of analysis is performed on the data in the table above, relating to the two roundabout system, it can be seen that there are four critical sections that are congested from instant 1500 to instant 4800:

- Crossroad 1: Entrance 4 with approximately 7 vehicles;
- Crossroad 3: Entrance 4 with approximately 11 vehicles;
- Crossroad 3: Section 13 with approximately 12 vehicles;
- Crossroad 3: Section 1 with approximately 6 vehicles.

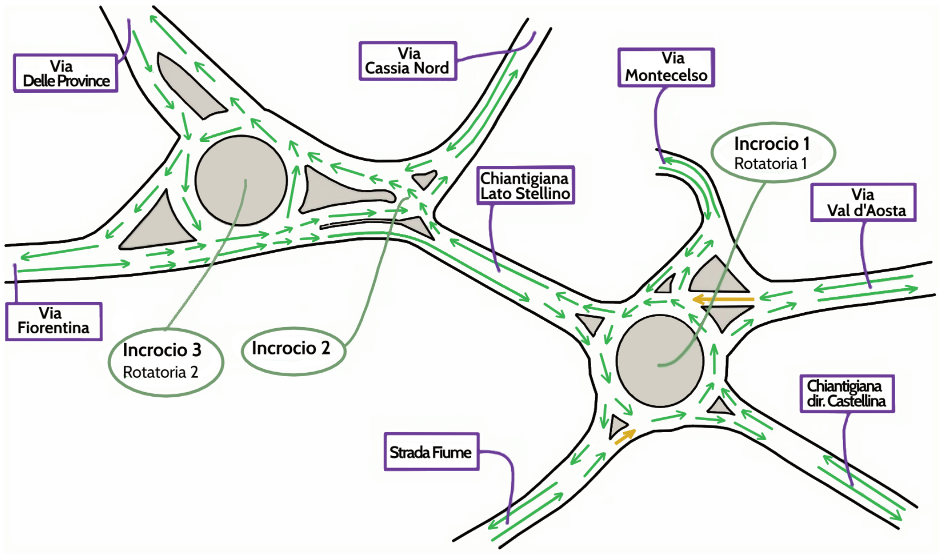
In this case the congestion at Entrance 4 of Roundabout 1 in the current system causes the saturation of Road 7 upstream and the congestion of Section 13 inside Roundabout 2, while the congestion at Entrance 4 of Roundabout 2 causes saturation of the upstream Street 16.

5. Graphic comparison

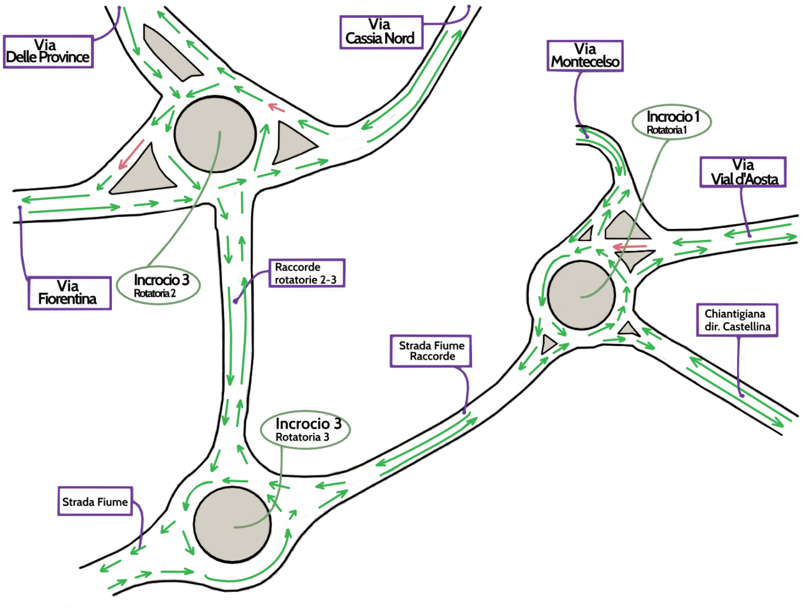
In this paragraph a small graphic comparison of the two models will be made by proposing the same instant of both the two roundabout and three roundabout models. At the bottom of the comparisons some issues previously revealed can be found, such as the peak of queuing vehicles.

5.1. Morning graphical comparison

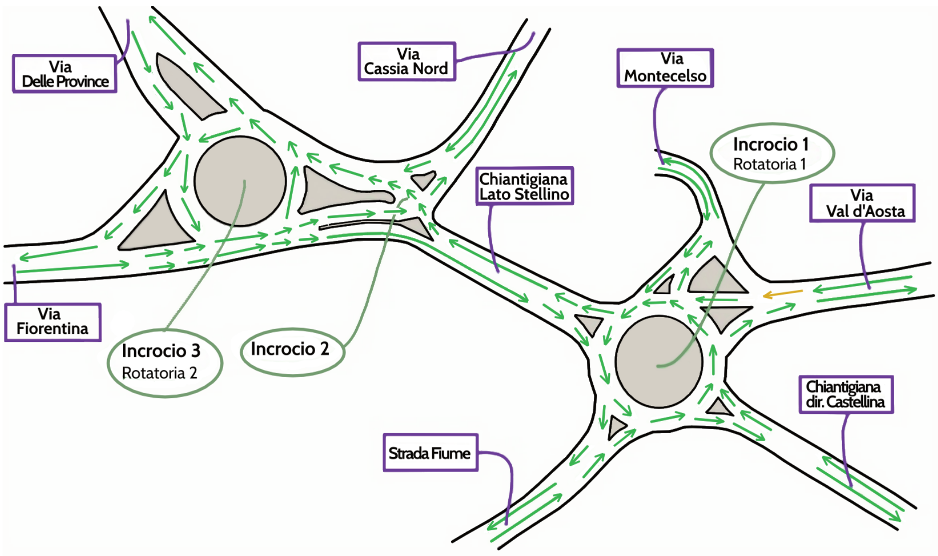
We begin with the morning slot which starts at 7.30. The interval this time is 600 seconds or 10 minutes.



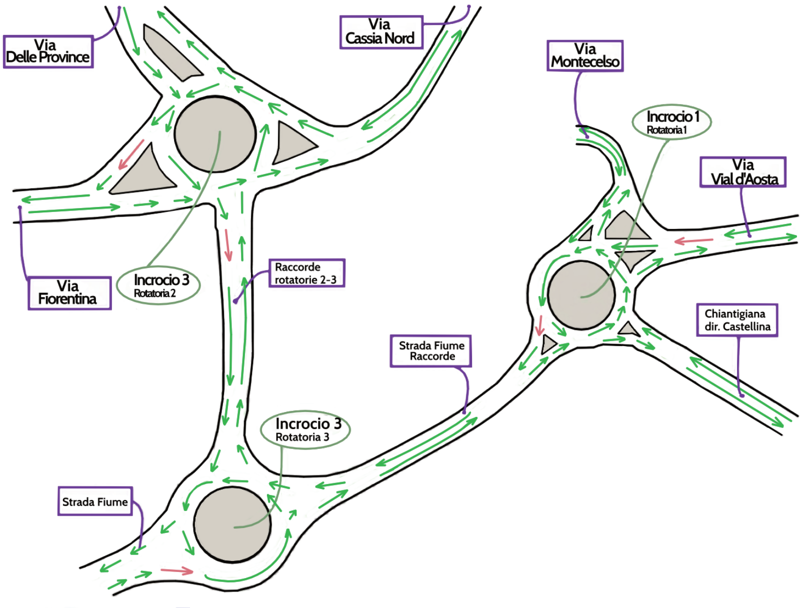
Simulation time: 600 seconds



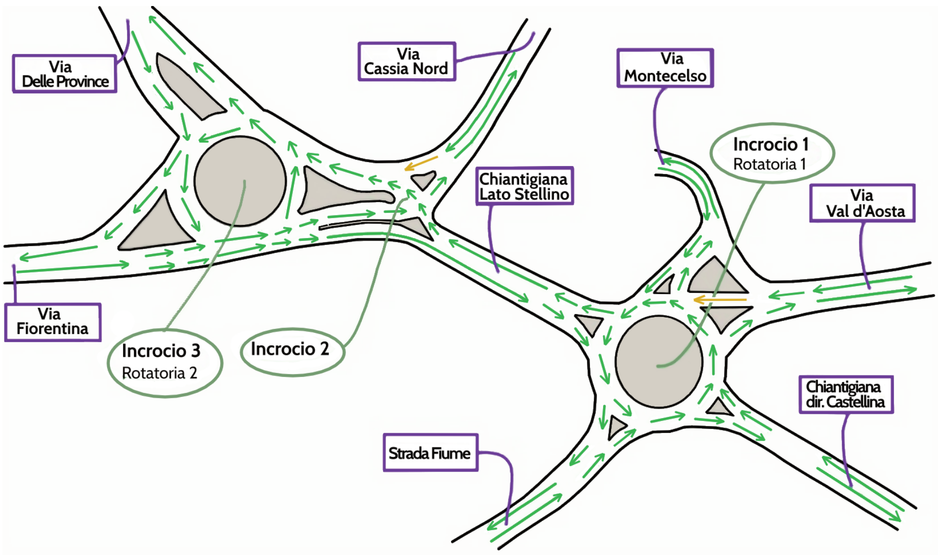
Simulation time: 600 seconds



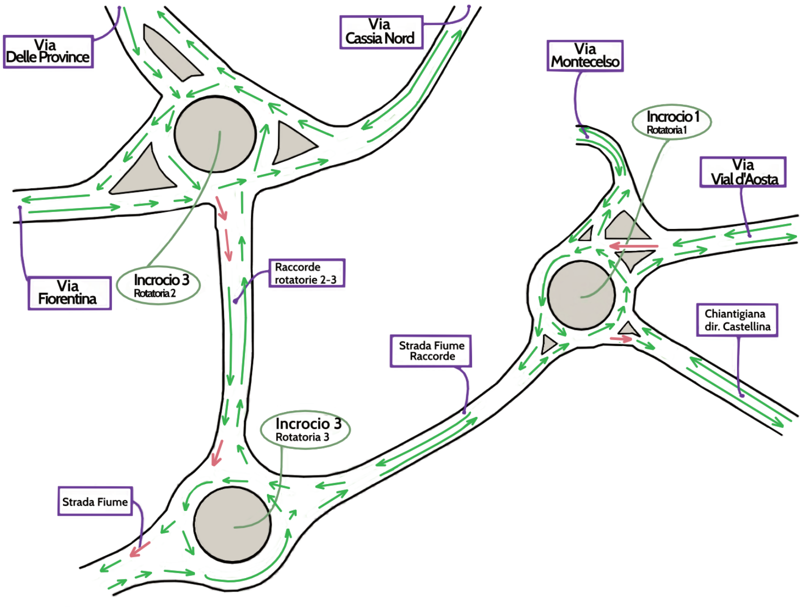
Simulation time: 1200 seconds



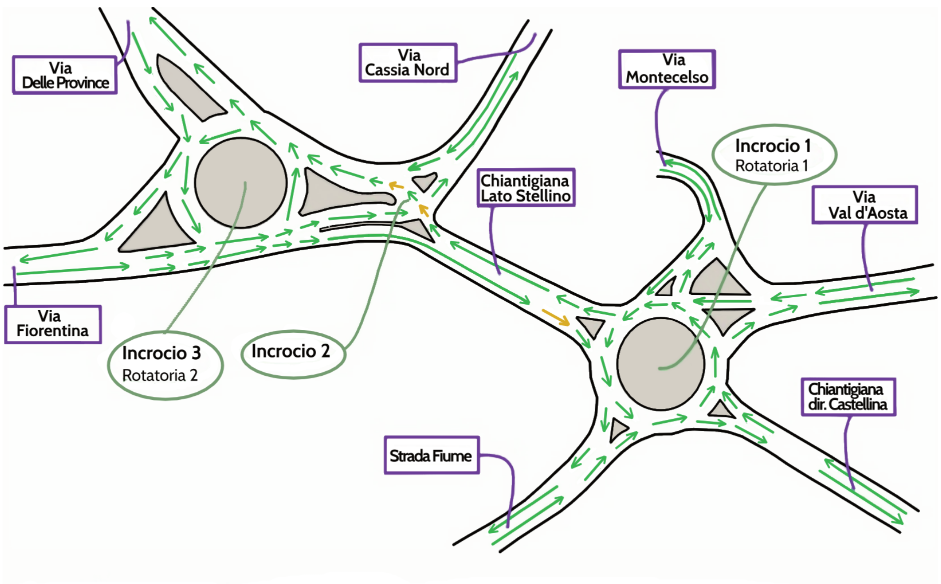
Simulation time: 1200 seconds



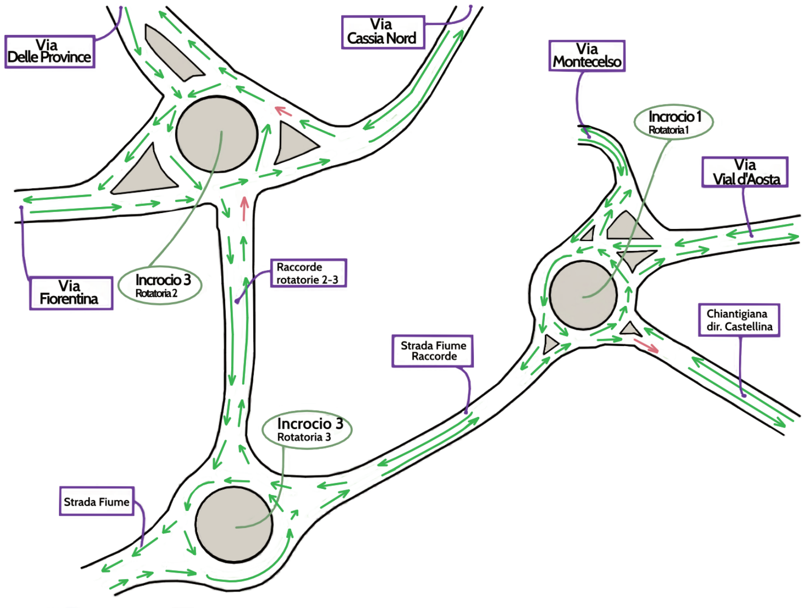
Simulation time: 1800 seconds



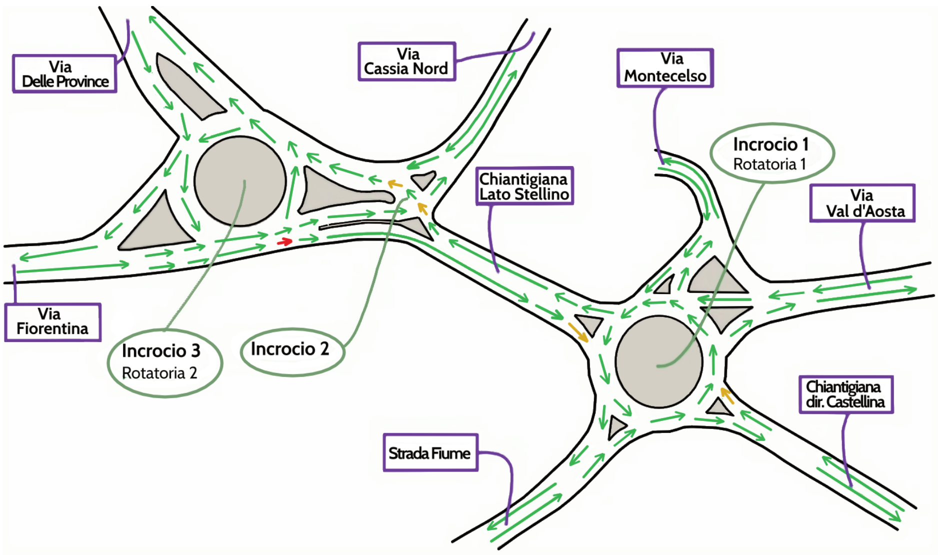
Simulation time: 1800 seconds



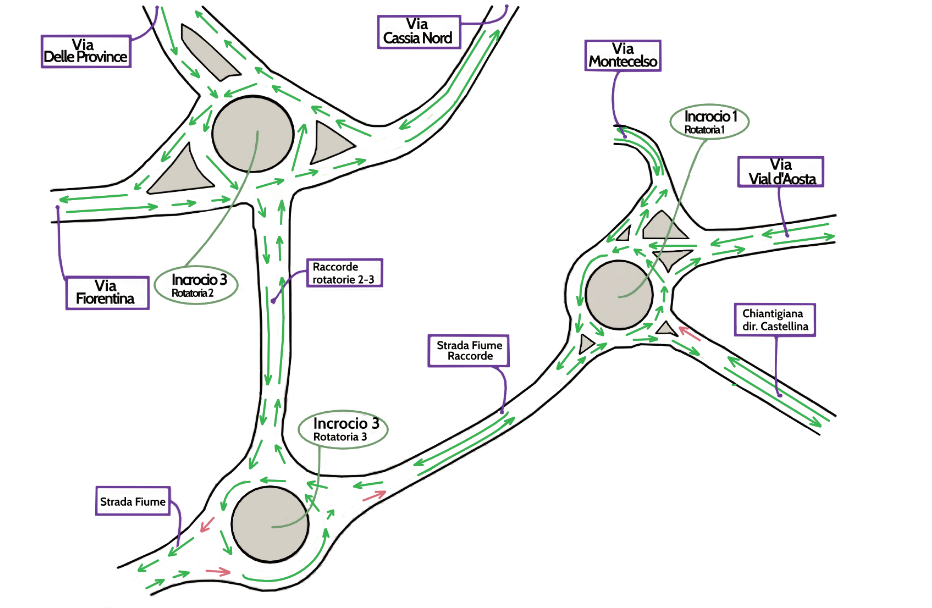
Simulation time: 2400 seconds



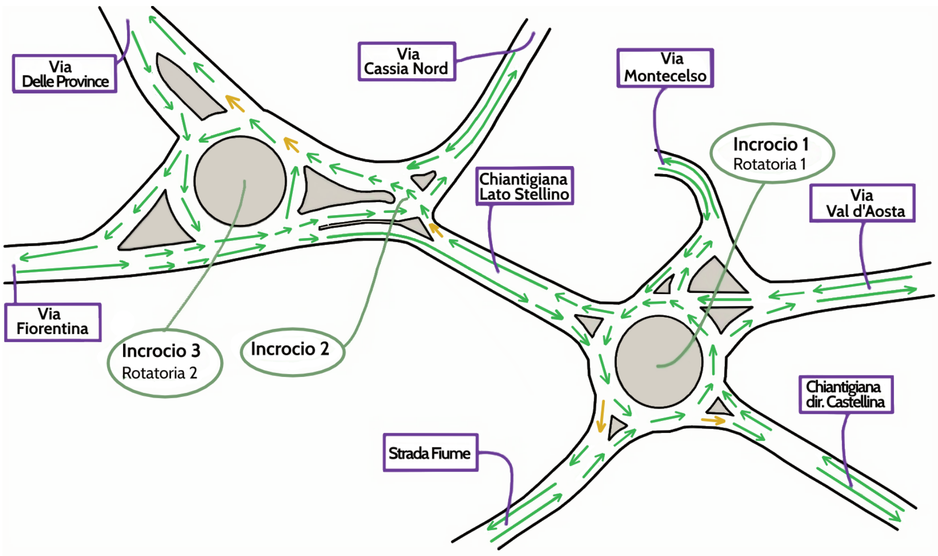
Simulation time: 2400 seconds



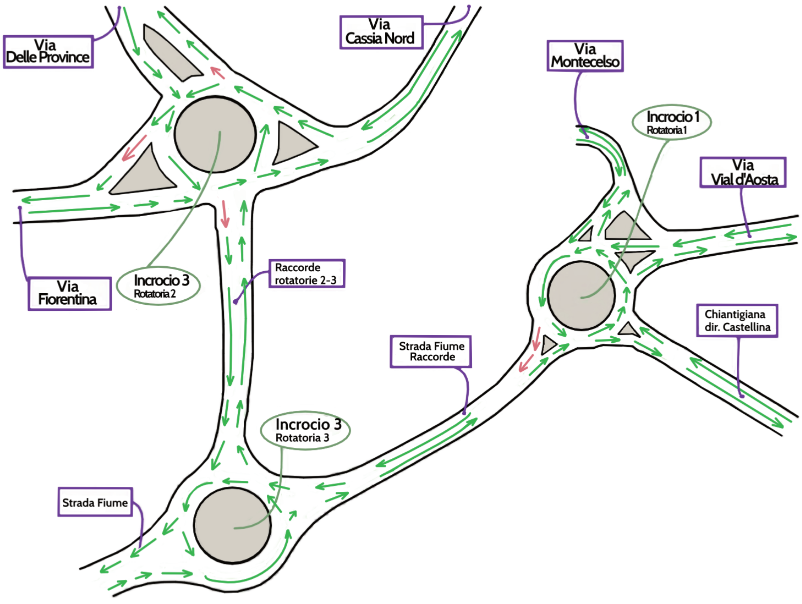
Simulation time: 3000 seconds



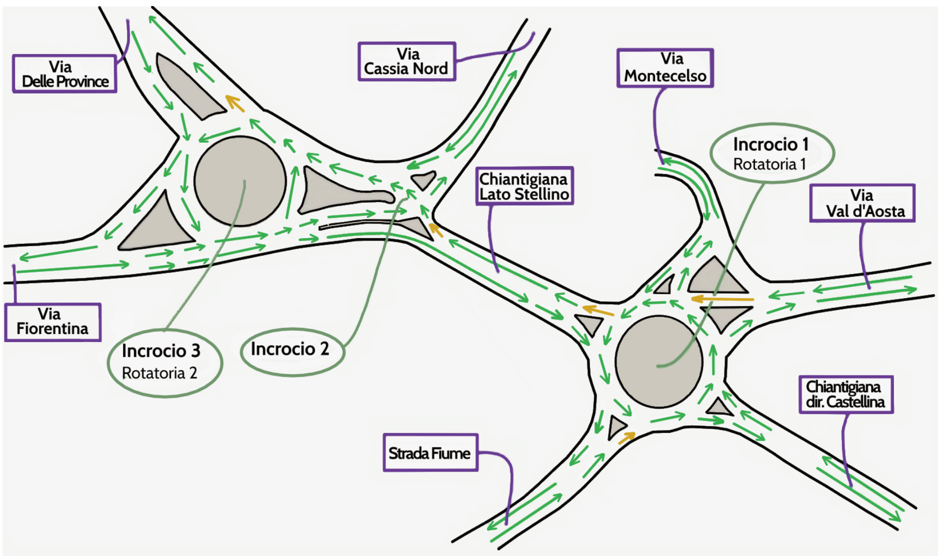
Simulation time: 3000 seconds



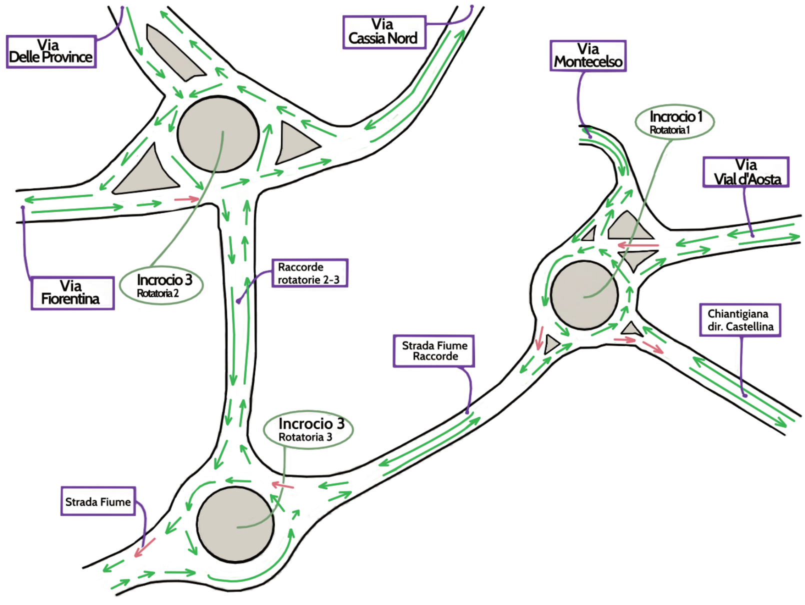
Simulation time: 3600 seconds



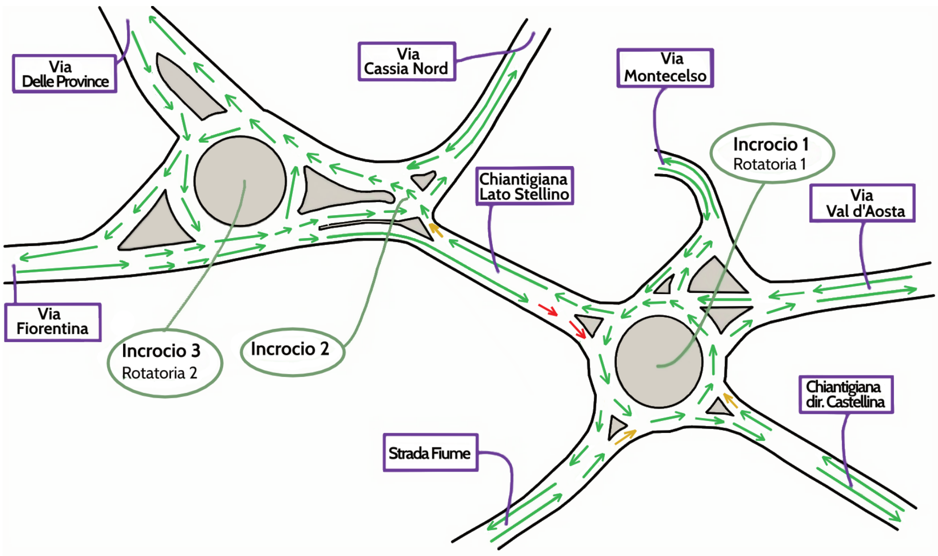
Simulation time: 3600 seconds



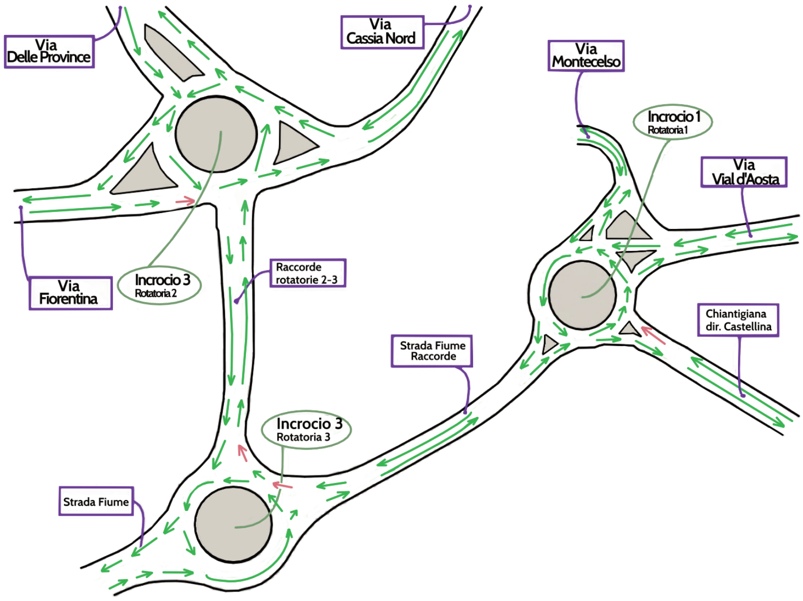
Simulation time: 4200 seconds



Simulation time: 4200 seconds

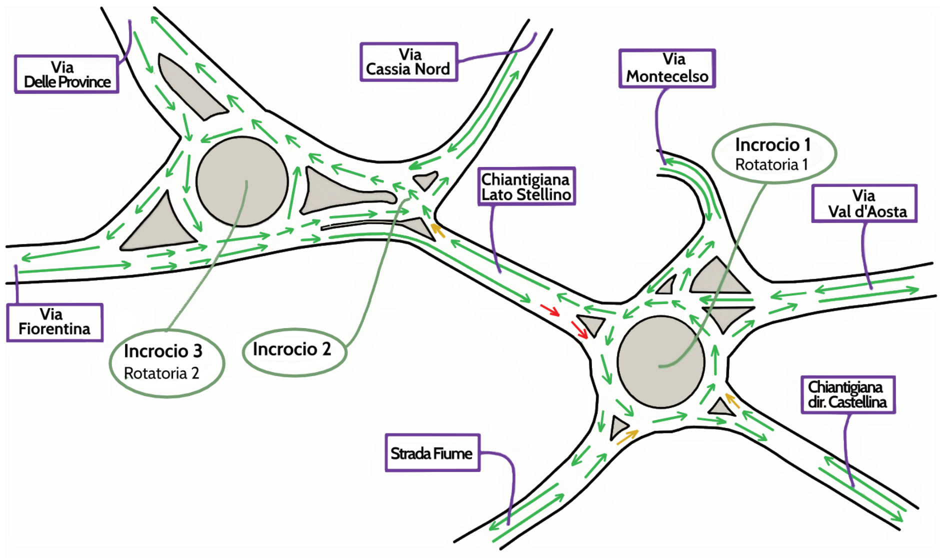


Simulation time: 4800 seconds



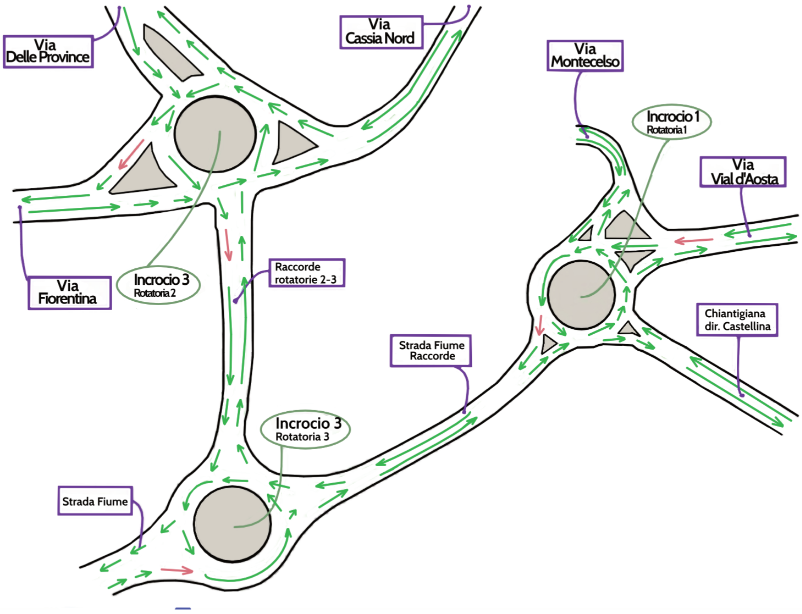
Simulation time: 4800 seconds

Figure 18. Morning graphic comparison every 10 minutes



Simulation time: 4800 seconds

The instants, also found in previous tables, are shown below with the situation of the two models during the peaks of vehicles in the 8.40 and 7.50 queues in the current system and in the three roundabout model, respectively.

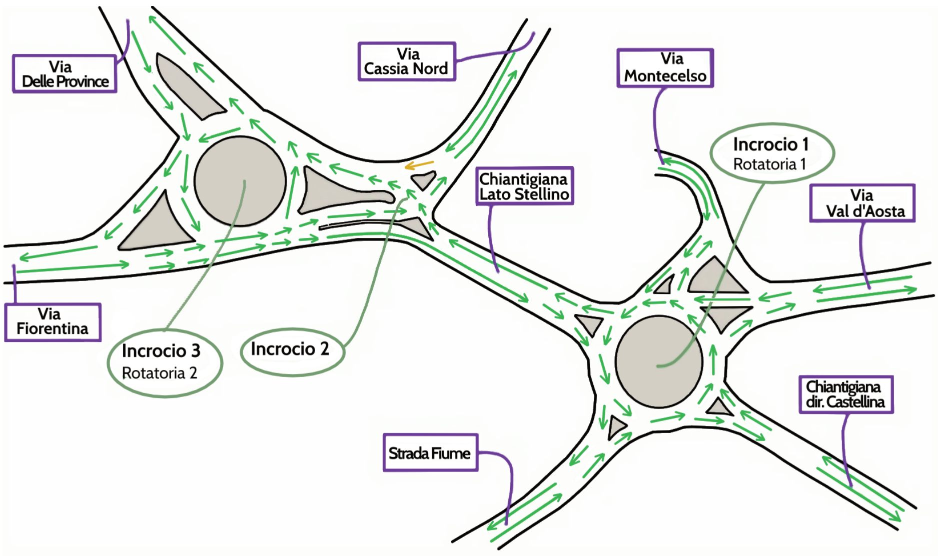


Simulation time: 1200 seconds

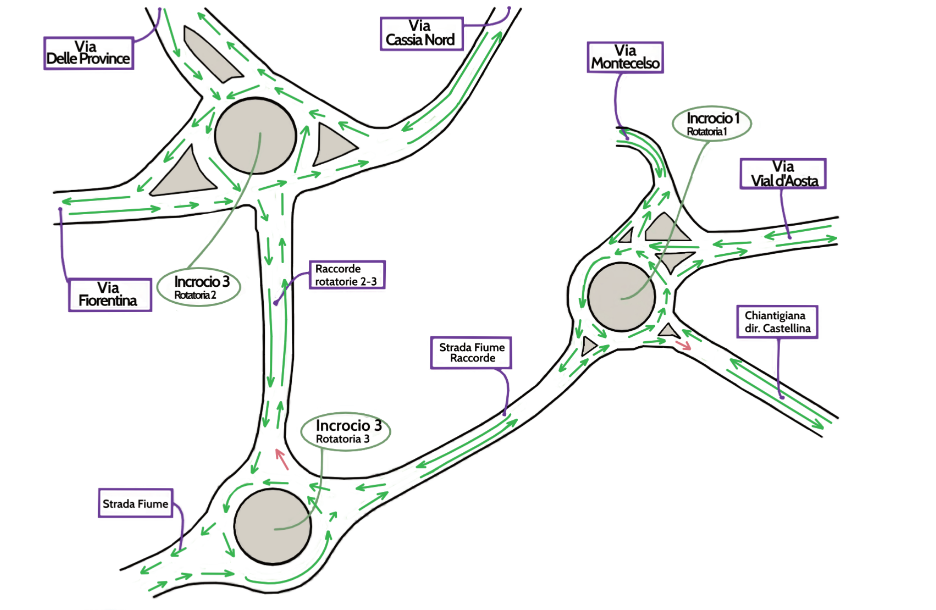
Figure 19. Queue peaks in the morning

5.2. Afternoon graphical comparison

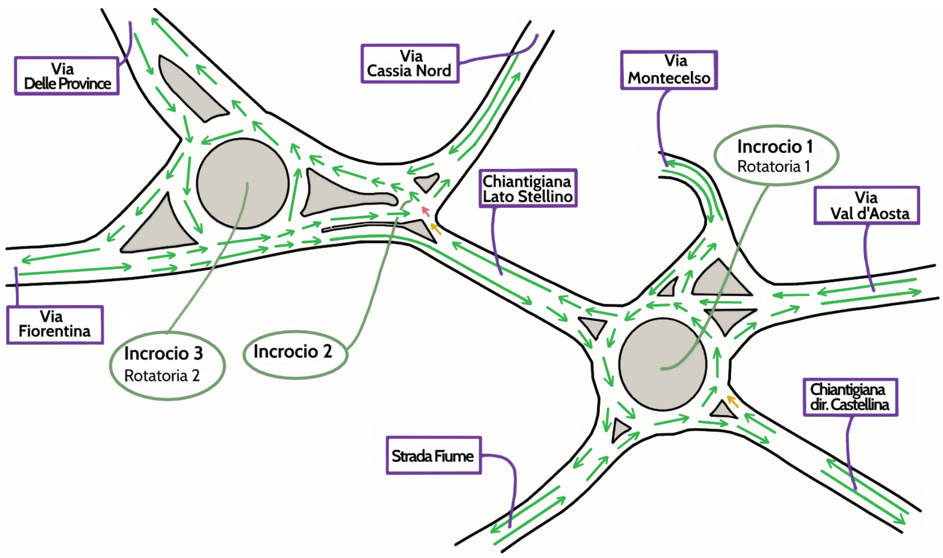
Let us now check the early afternoon slot which starts at 12.00. An interval of 10 minutes is always considered.



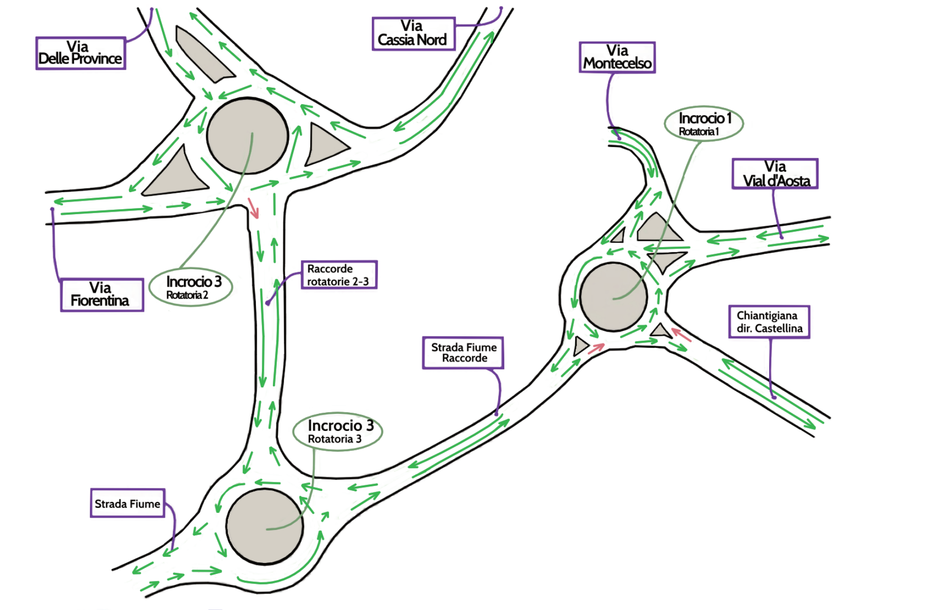
Simulation time: 600 seconds



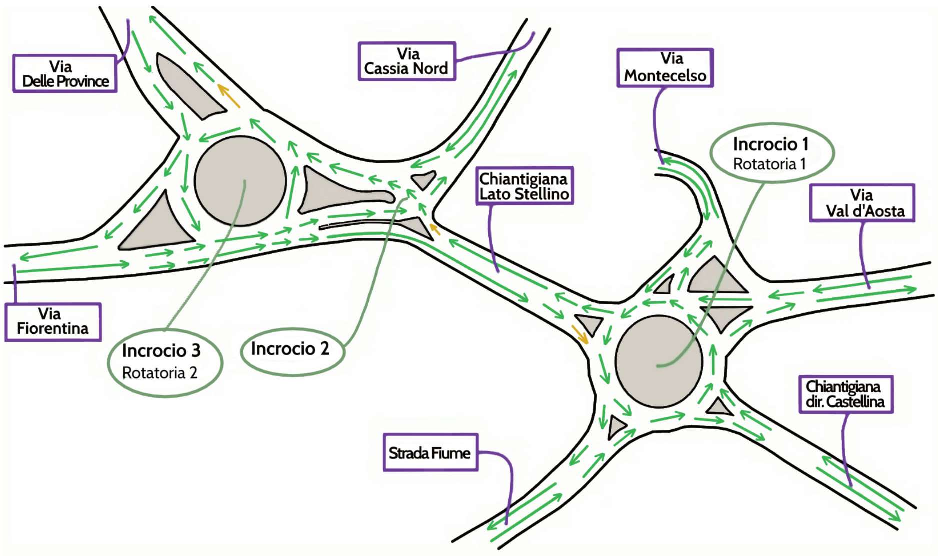
Simulation time: 600 seconds



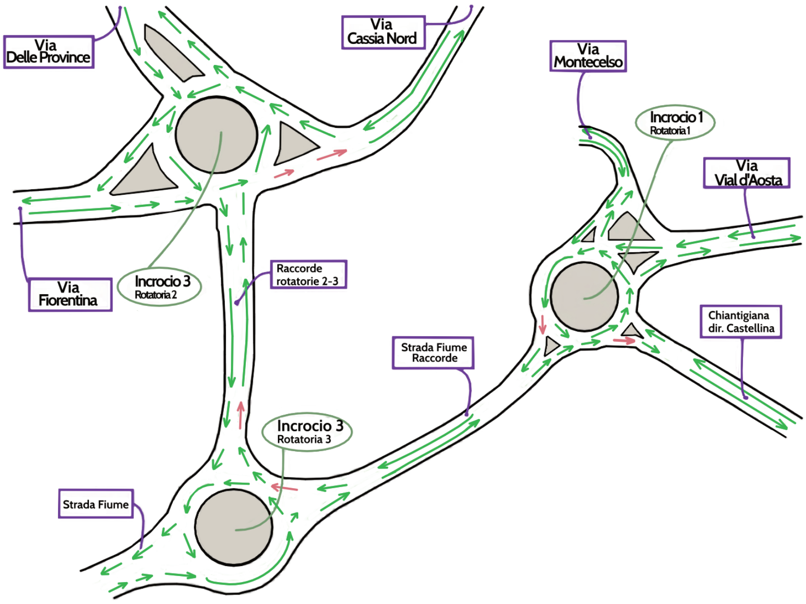
Simulation time: 1200 seconds



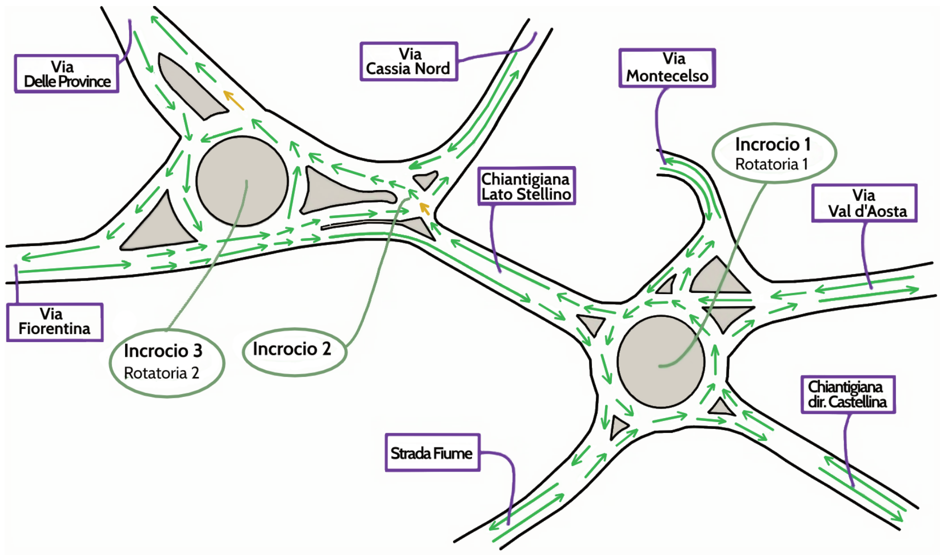
Simulation time: 1200 seconds



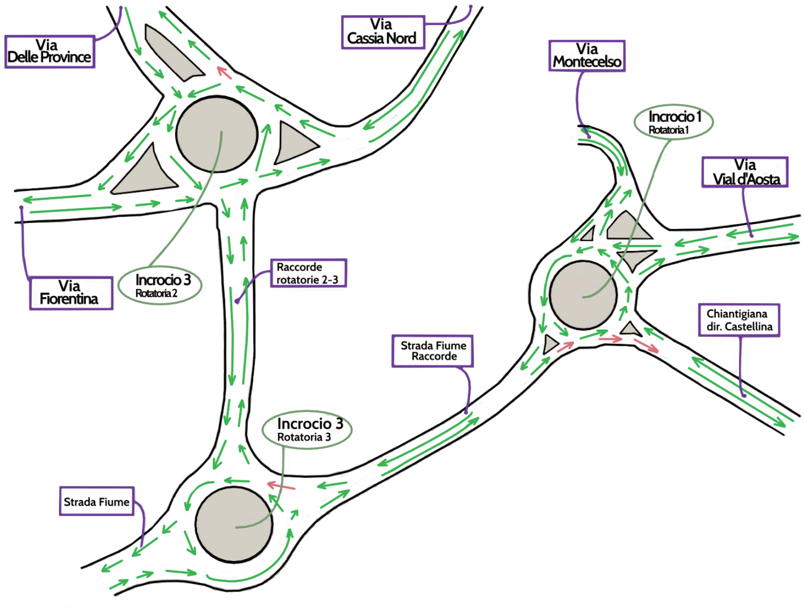
Simulation time: 1800 seconds



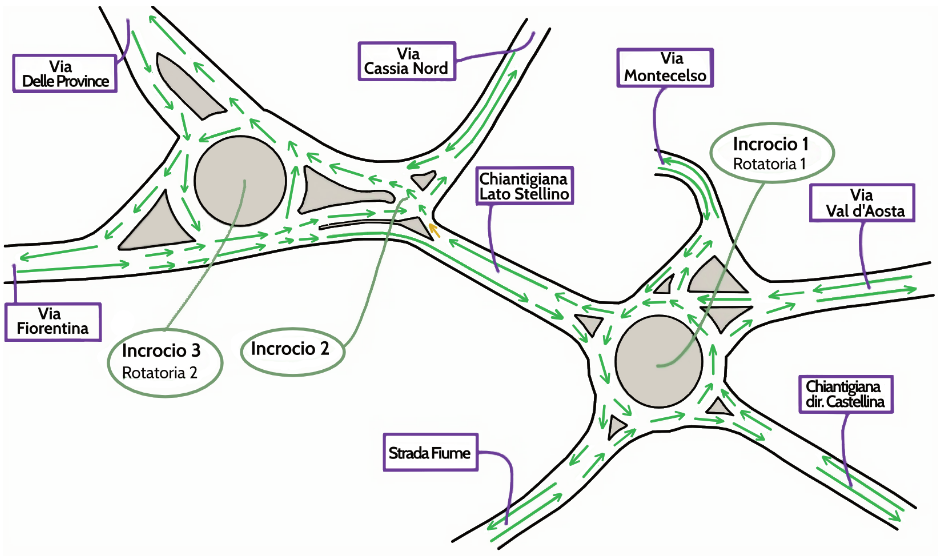
Simulation time: 1800 seconds



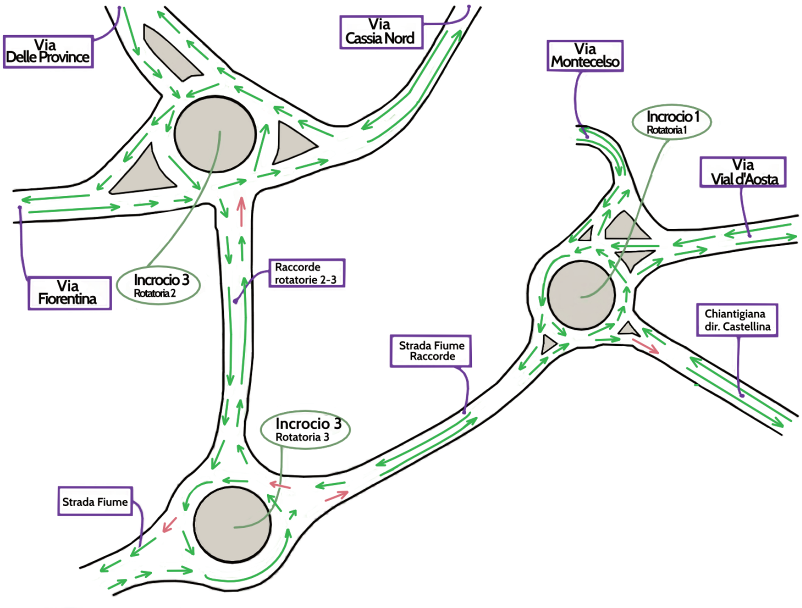
Simulation time: 2400 seconds



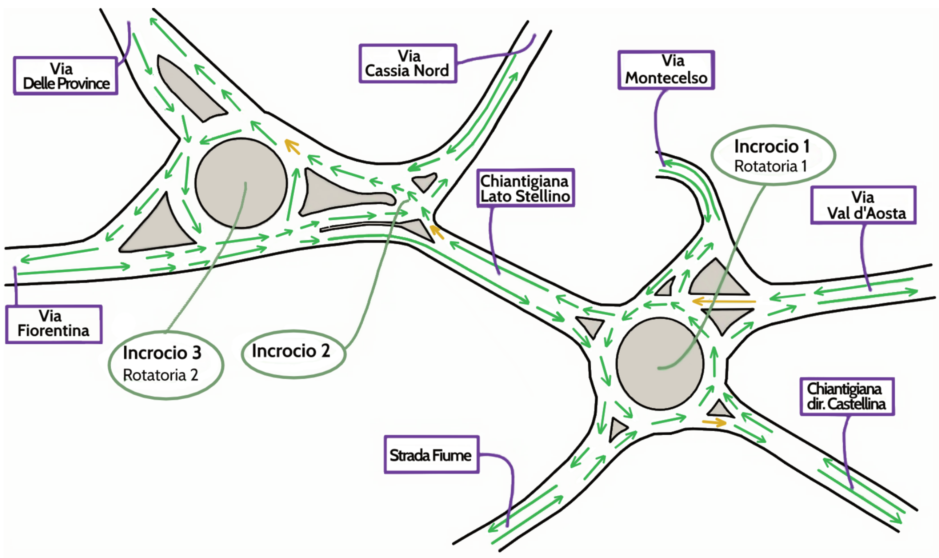
Simulation time: 2400 seconds



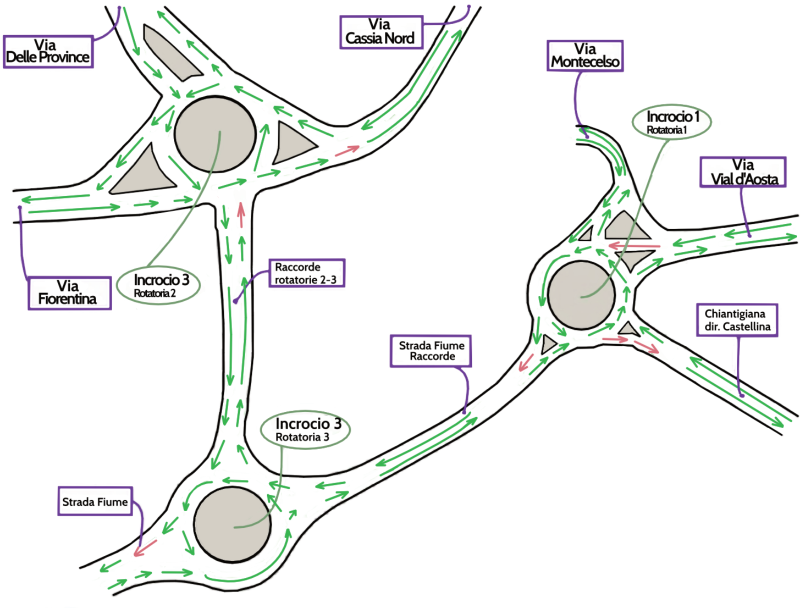
Simulation time: 3000 seconds



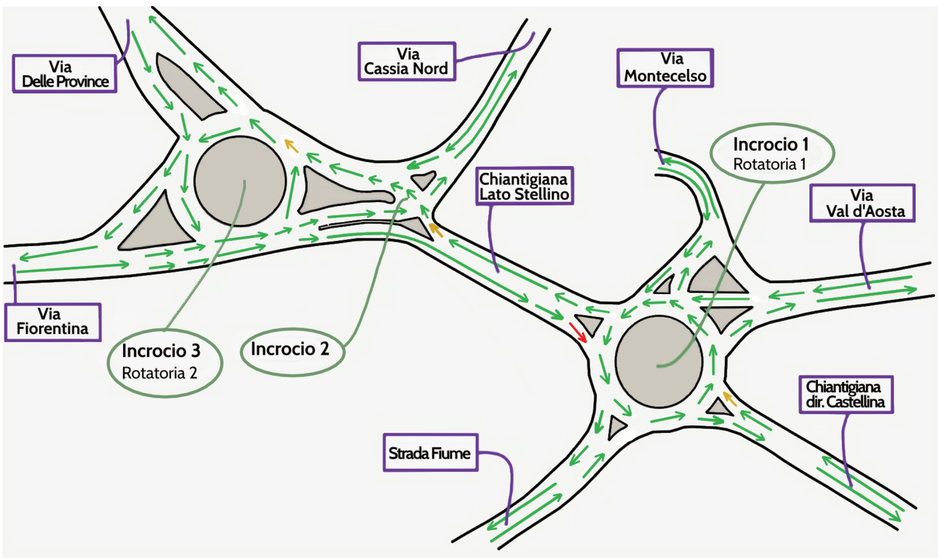
Simulation time: 3000 seconds



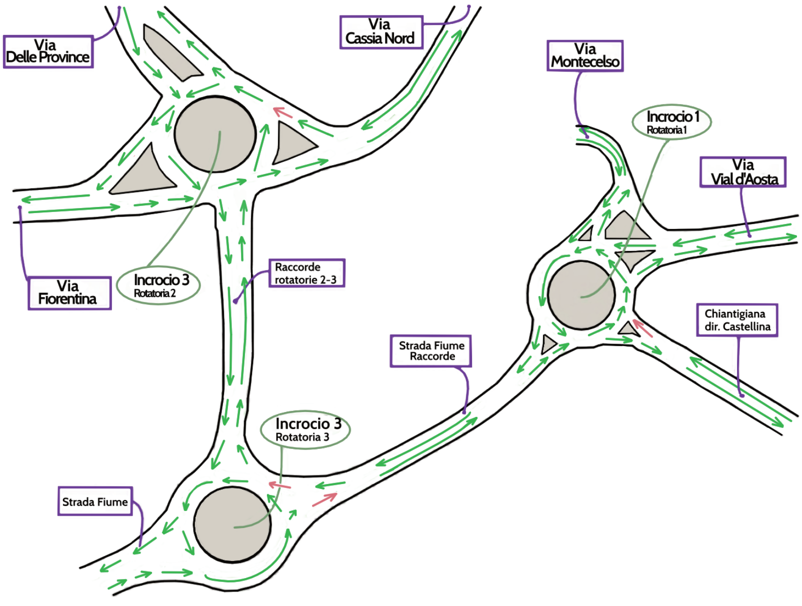
Simulation time: 3600 seconds



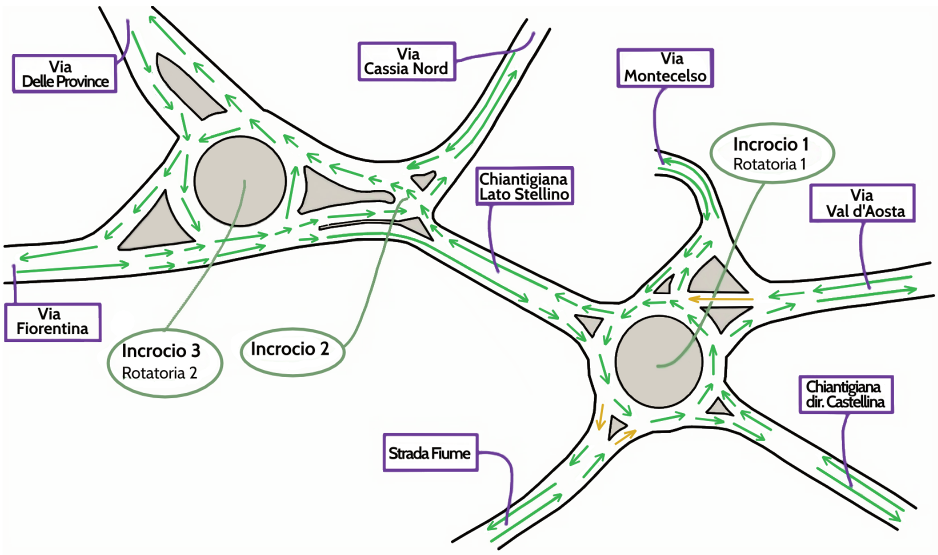
Simulation time: 3600 seconds



Simulation time: 4200 seconds



Simulation time: 4200 seconds



Simulation time: 4800 seconds

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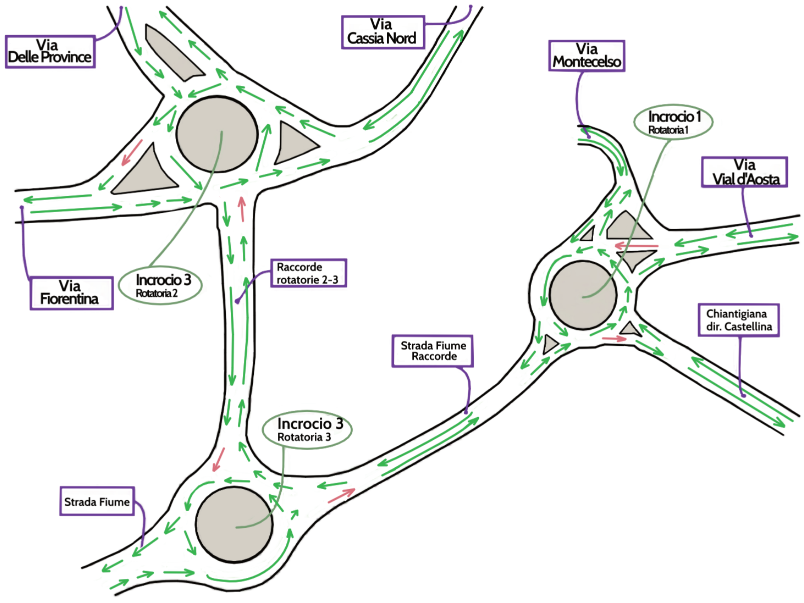
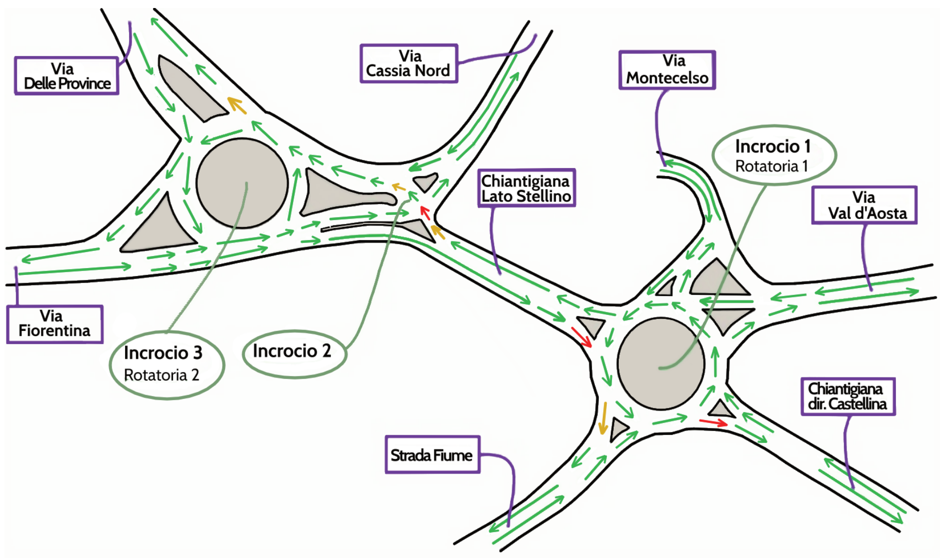


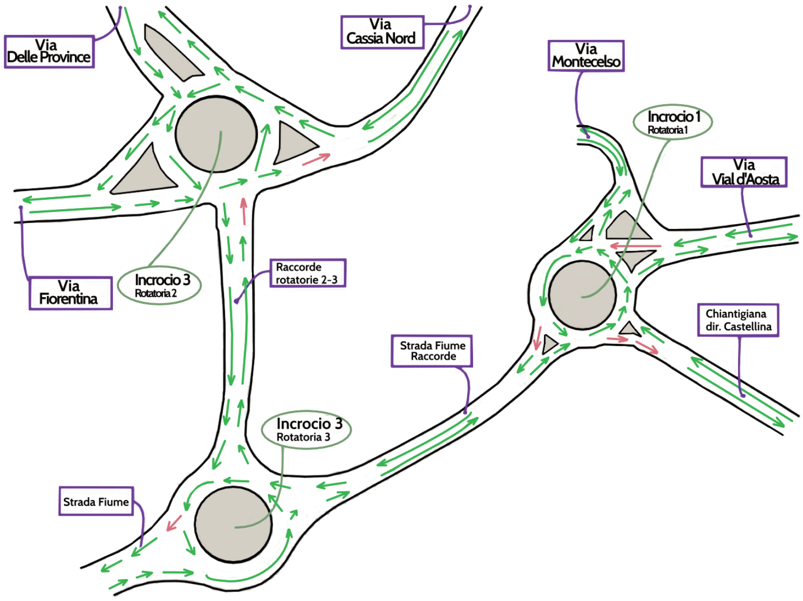
Simulation time: 4800 seconds

Figure 20. Graphic comparison of the afternoon every 10 minutes

The peaks of queues in the afternoon are shown with the peak at 13.05 in the two roundabout system and those of 12.15 and 13.00 (only the latter is considered) in the three-roundabout system.



Simulation time: 3900 seconds

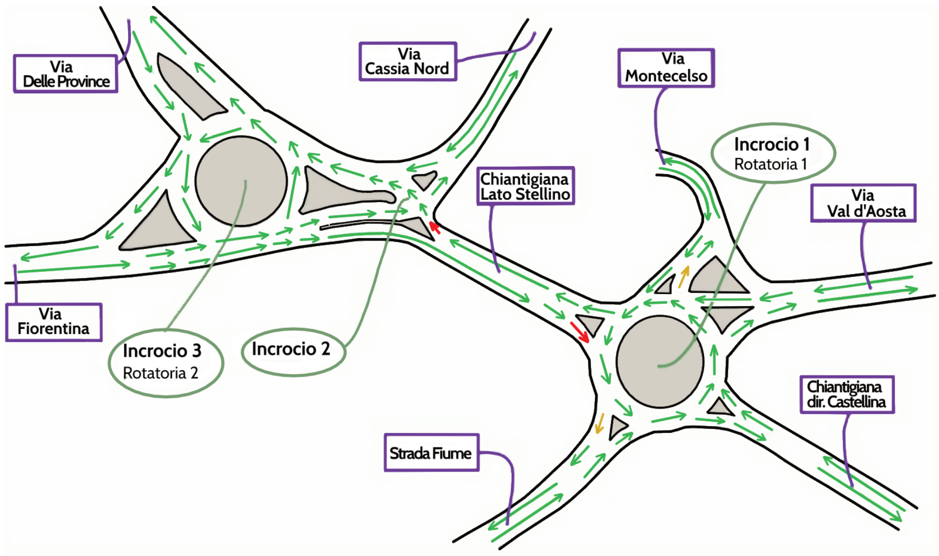


Simulation time: 3600 seconds

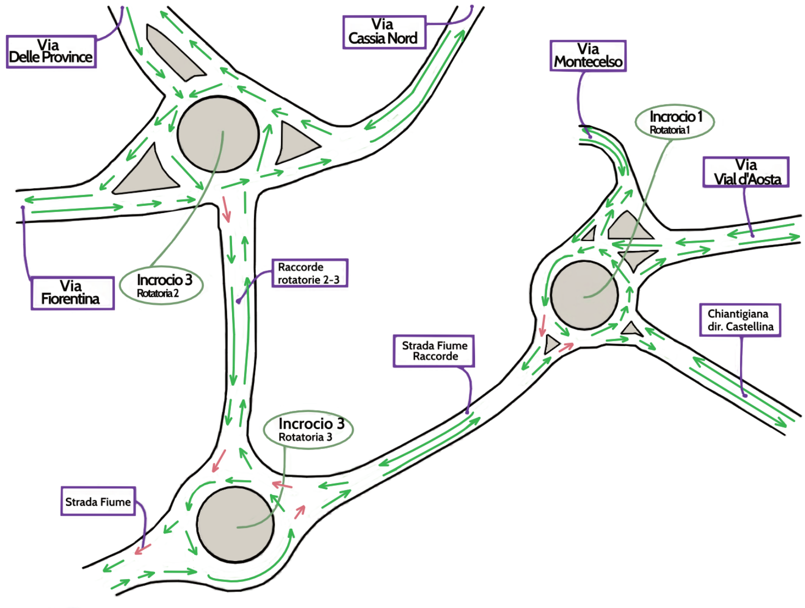
Figure 21. Queue peaks in the afternoon

5.3. Evening graphical comparison

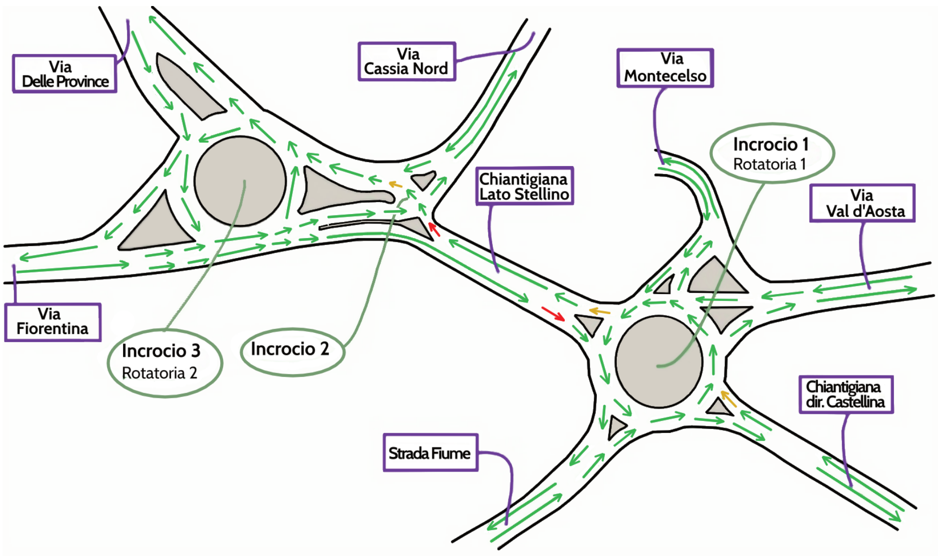
We conclude with the evening arc that starts at 5.30 pm with 10-minute intervals.



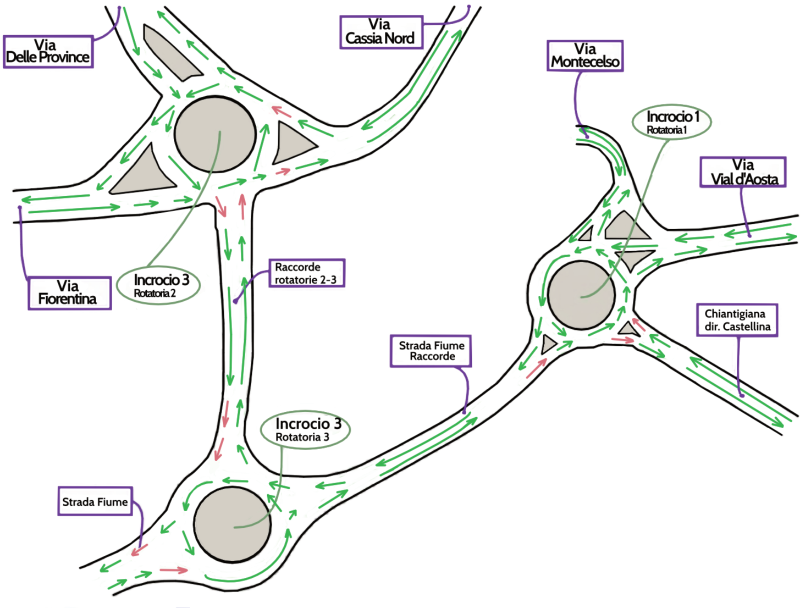
Simulation time: 600 seconds



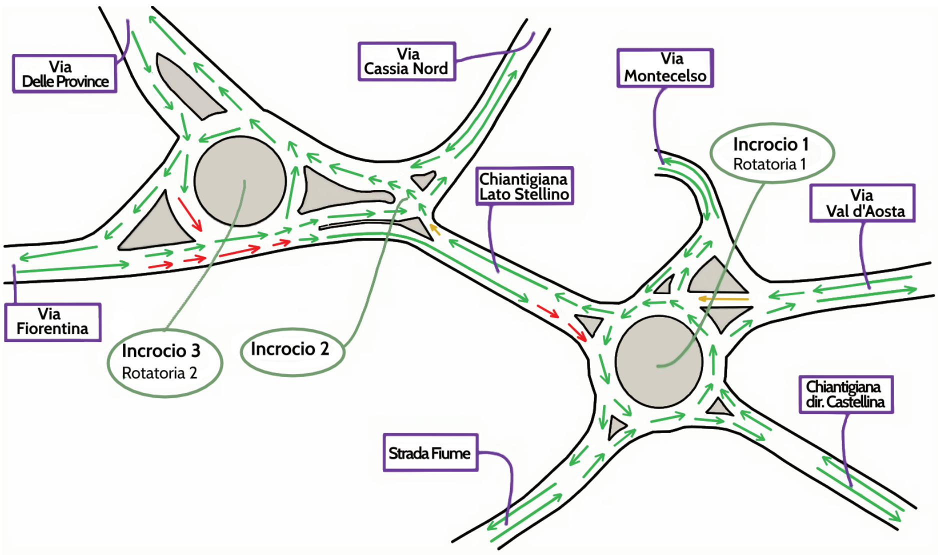
Simulation time: 600 seconds



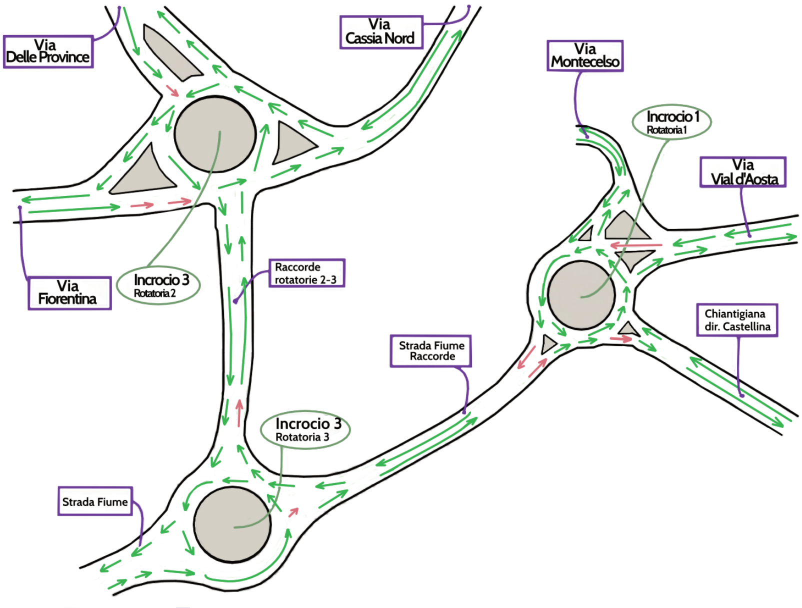
Simulation time: 1200 seconds



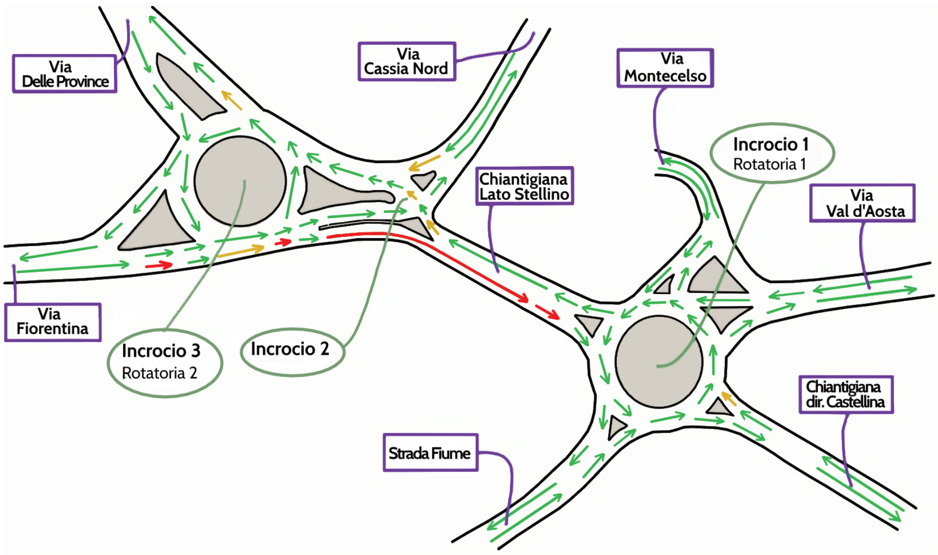
Simulation time: 1200 seconds



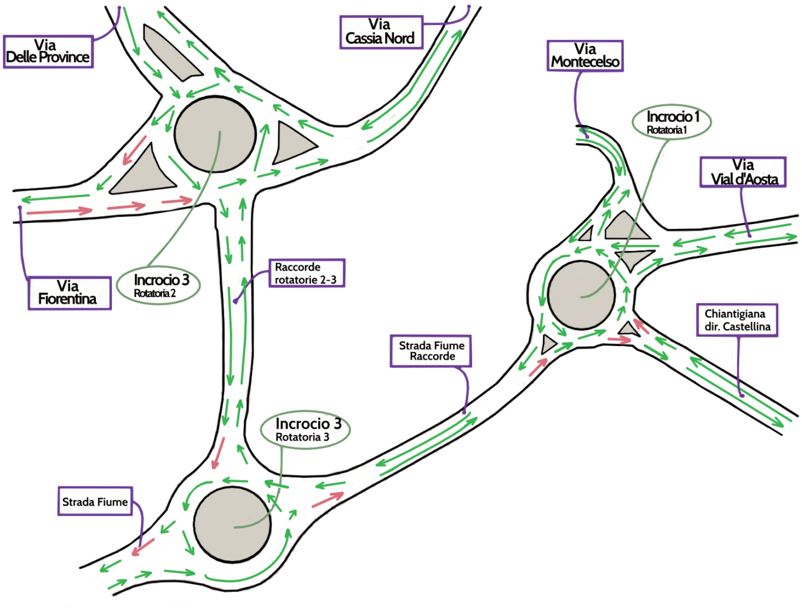
Simulation time: 1800 seconds



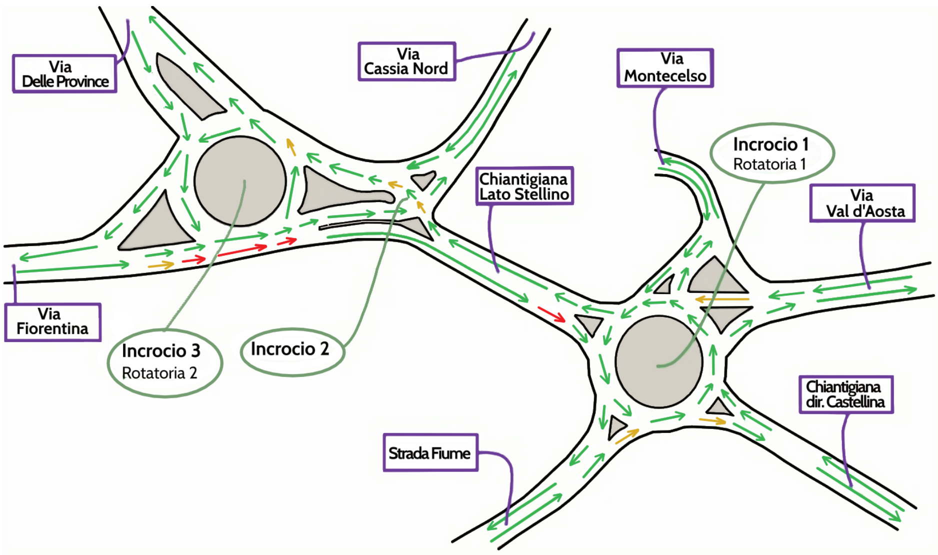
Simulation time: 1800 seconds



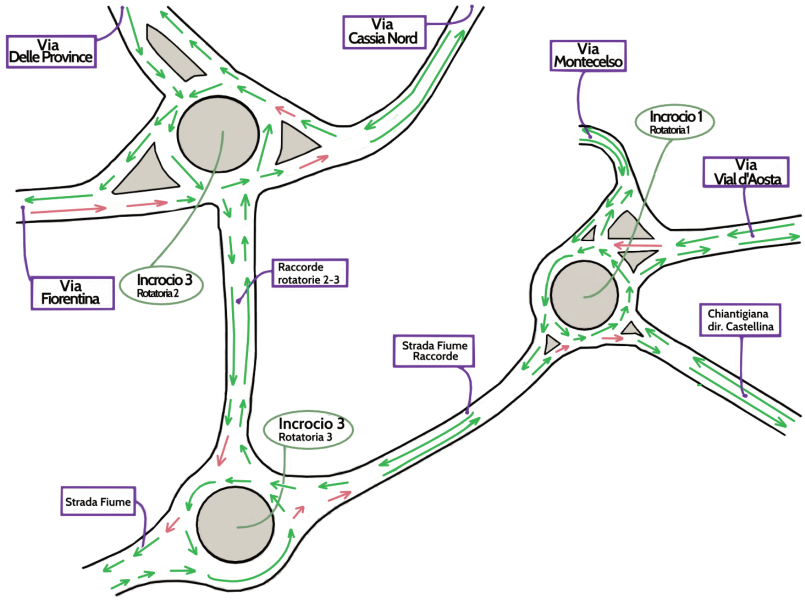
Simulation time: 2400 seconds



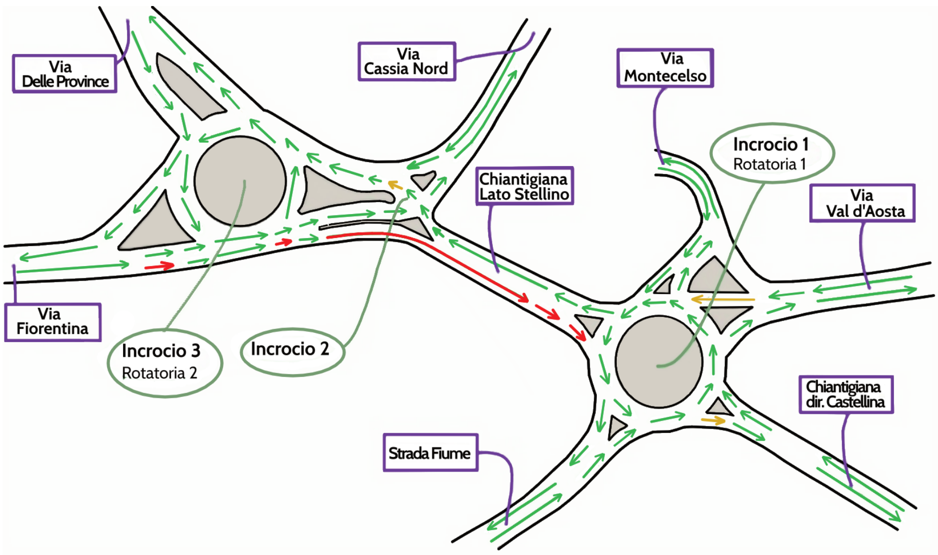
Simulation time: 2400 seconds



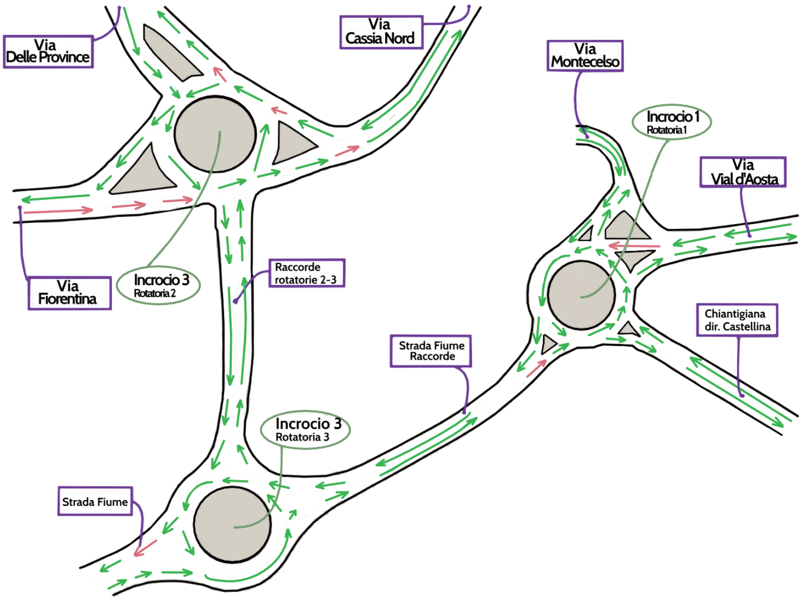
Simulation time: 3000 seconds



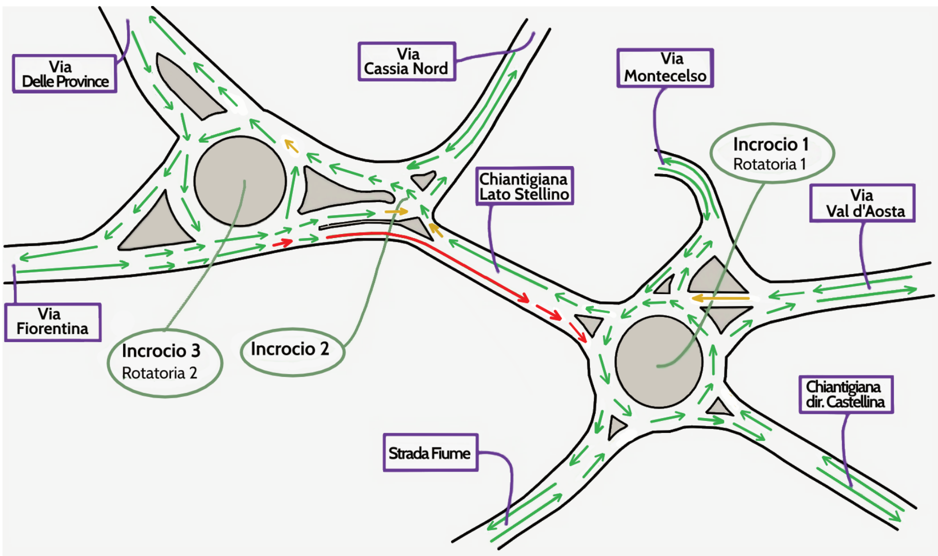
Simulation time: 3000 seconds



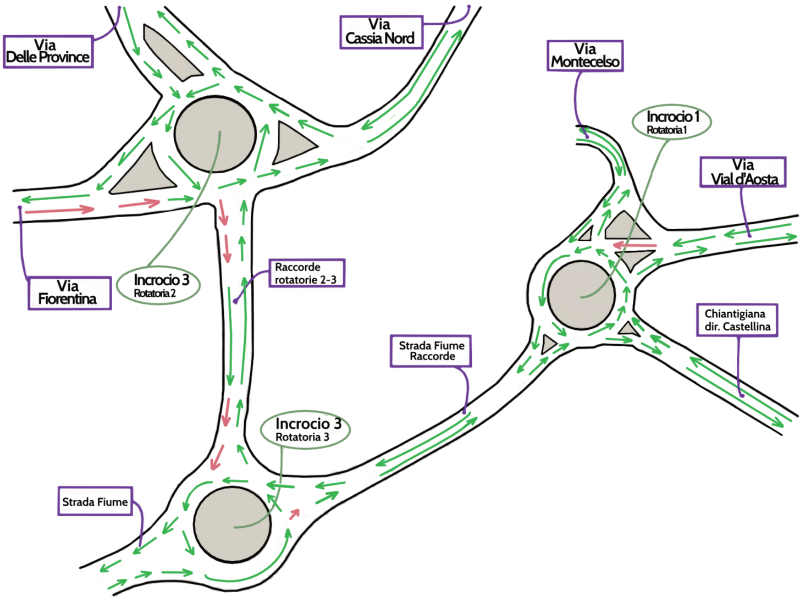
Simulation time: 3600 seconds



Simulation time: 3600 seconds



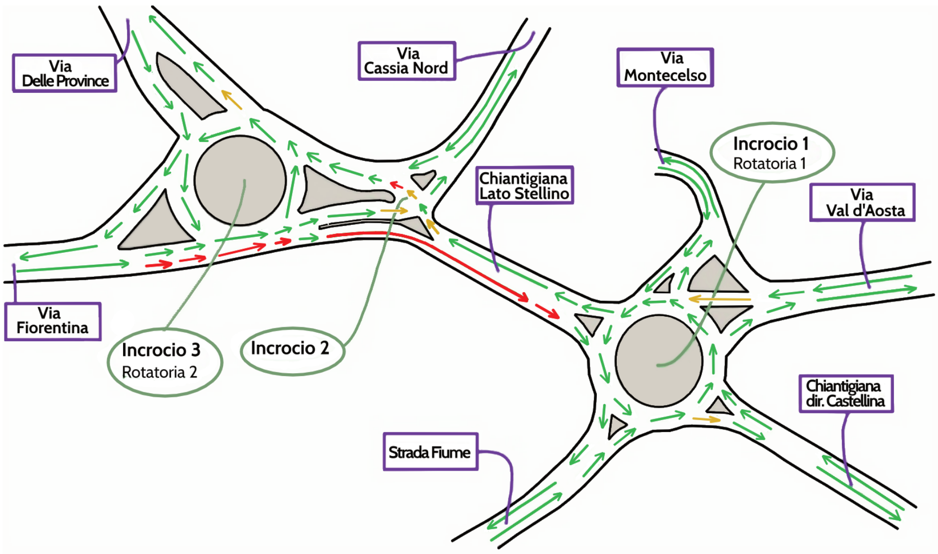
Simulation time: 4200 seconds



Simulation time: 4200 seconds

Figure 22. Graphic comparison of the evening every 10 minutes

Let us now look at the peaks of vehicles in the queue at 18.00 and 18.25 (the latter is considered) in the two-roundabout system and at 17.55 in the three-roundabout system. The exact moment (after 2010 seconds) in which Road 18, coming from Via Fiorentina, is compromised because it is saturated is highlighted below instead.



Simulation time: 3300 seconds

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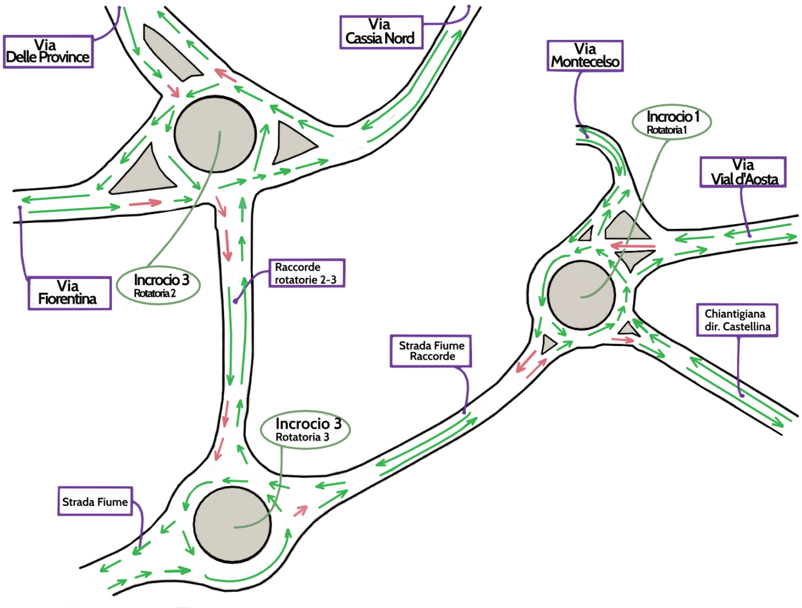

Simulation time: 1500 seconds

Figure 23. Queue peaks in the evening

6. Conclusions

In some previous works we defined a method for the construction of vehicle traffic system simulators based on complex queue network models. In this work we applied this technique to perform a comparison between two models of vehicular traffic appearing to be alternatives for the management of an urban area located in Siena, Italy, northern area. In fact, we compared the current management system, which we named a two-roundabout system and an alternative system foreseen by the new PRG of the city, which we called a three-roundabout system. We simulated the two traffic patterns in the three time slots: morning, afternoon and evening. The analysis of the tracing of vehicular flows in the simulations provided us with the following data on the traffic congestion levels.

1) **Morning comparison**
   a) Three-roundabout system: There are queues of vehicles, but they are of little importance as the number of vehicles involved is very low. There is only one queue of 8 vehicles at Entrance 2 of Roundabout 1. The traffic flows in the system are smooth.
   b) Two-roundabout system: there are less frequent, but more important vehicle queues compared to what happens in the 3 roundabout system. There are 5 queue events with the number of vehicles involved ranging from 6 to 8. Traffic flows are smaller in this model also because the two-roundabout system is less extensive than the three-roundabout model.

2) **Afternoon comparison**
   a) Three-roundabout system: there are frequent queues of vehicles, but they are sparse in importance, these are queues that generally consist of 2 vehicles and that appear to be distributed throughout the system. Traffic flows in the system are smooth.
   b) Two-roundabout system: there are frequent queues of low intensity except the instant of 3900 of the time slot with 6 queues located between Intersection 1 and Intersection 2 of the system.
3) **Evening comparison**
   a) Three-roundabout system: the system internally has a medium congestion level with numerous queues of mild intensity, the critical point is the entrance to the system from via Fiorentina which appears to be totally congested.
   b) Two-roundabout system: the system is congested both internally and in the entry point from via Fiorentina.

This analysis shows that the three-roundabout model envisaged by the PRG would improve the management of vehicular flows in Siena northern area, because it would lower the current vehicular traffic congestion level, but would not solve this problem. In fact, even the new three-roundabout model would be subject to major traffic congestion events that would occur in the evening phase in Via Fiorentina. This congestion would be caused by the slowing of vehicles in the inlet flow to Roundabout 2.

References

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[2] Pasini L 2018 *TASK Quart.* **22** (2) 135
[3] Pasini L and Sabatini S 2016 *TASK Quart.* **20** (1) 9
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[6] Pasini L, Rietti F M and Allegretto F 2016 *TASK Quart.* **20** (3) 273
[7] Pasini L and Feliziani S 2010 *TASK Quart.* **14** (4) 405
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[9] D'Ambrogio A, Iazeolla G, Pasini L and Pieroni A 2009 *Simulation Modelling Practice* **17** (4) 625