Solving a Traffic Congestion Problem at T- intersections using AnyLogic Simulation

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***Abstract*—Beyond its significance in urban planning and traffic engineering, the optimal design of road networks is crucial for the uninterrupted flow of traffic. Traffic congestion results in increased travel times and waiting times as well as higher CO_2 emissions. It is therefore imperative to study and optimize the traffic flow through roads and junctions to avoid such conditions. In this paper, a highly congested T-intersection in Narvik, Norway, is analyzed and several alternative plans are tested to reduce the travel time through the junction and the waiting time for cars in queues. The process begins with the collection of traffic data to estimate the current waiting times and understand the queuing problem. The current state is modeled in AnyLogic to simulate the actual conditions at the intersection. Two alternate solutions are then presented and analyzed. One is the use of traffic lights, and the other is the installation of a roundabout. The waiting times and queues associated with the two alternatives are compared with the current state to determine the better alternative. This paper presents the effectiveness of using simulation to solve the traffic congestion problems at T-junctions, and the method can be applied to various similar problems.**

I. INTRODUCTION

Traffic management involves the proper design and effective management of road networks so that traffic congestion can be reduced, waiting times can be decreased, and queues can be shortened or eliminated, while at the same time, maintaining the safety of the road users. In urban areas, traffic congestion is an ever-increasing problem and requires an effective approach to test and optimize several alternative solutions to minimize the impact of traffic congestion. Unfavorable delays in traffic cause higher CO_2 emissions in the surrounding areas and decrease the traffic efficiency and the driving experience of road users. Moreover, traffic congestion seriously hampers the rescue and emergency services, which renders timely aid highly improbable in most cases.

Traffic flow into and out of urban centers has been of primary interest in traffic engineering. The study of traffic characteristics across different types of intersections has led to the development of refined traffic management practices that are used worldwide today. Moreover, another aspect of primary interest in this subject has been the variation in traffic density, spacing, and speed variations at different times of the day, different days of the week, and different seasons of the year. Usually, the rush hours in the morning and afternoon exhibit the worst traffic congestion in urban areas, while traffic on highways experiences high congestion during the daily rush hours as well as at the start and the end of weekends. To understand and tackle congestion problems, it is important to understand the characteristics of the traffic system in terms of preferred speeds, preferred routes, arrival rates, spacing, and similar behaviors. Extensive studies in this domain have led to immense developments in traffic engineering. Today, the use of cutting-edge technologies for aiding the management of traffic flows in both active and passive ways has been widely practiced in all kinds of road networks.

One major cause of increased traffic congestion in urban and semi-urban areas is the significant increase of private vehicles, which is disproportionate to the extent and intent of the infrastructural growth in supporting road networks. Road infrastructure simply cannot keep pace with the steep rise in private vehicles, and new methods and solutions must thus be developed, tested, and refined to increase the use of the existing road infrastructure.

In this paper, several alternative solutions are discussed and compared for a real-world T-intersection between Narvik and Ankenes in Nordland county, Norway. The T-intersection faces frequent queuing and congestion problems due to a high traffic volume on the primary road, E6, and a high number of adjacent large shops and parking areas.

II. LITERATURE REVIEW

Obtaining accurate and reliable traffic data is imperative to studying and solving the traffic congestion problem. There have been multiple studies discussing various methods that can be used to collect traffic data. In this paper, the traffic data was obtained by two main methods, namely, the data collected from multiple manual observations and the publicly accessible data from the Norwegian Public Roads Administration [4]. There are a variety of methods to detect and measure traffic on roads. One widely used method is the use of inductive loop sensors to detect the direction, speed, and spacing of traffic on a road [5]. Extensive studies over the years in traffic flow theory have established that the flow of traffic can be mathematically modeled accurately by using the Poisson distribution [6]. In this regard, AnyLogic uses Poisson distribution to define arrival rates in the Road Traffic Library [7]. Furthermore, it is well-established that traffic systems are discrete event systems [8]. Through 50 years of development, this subject area has made significant advancements.

In our case study, traffic signals and roundabouts are important. The capacity and timing analysis of traffic signals may provide important insights into how traffic congestion can be dealt with [9], which has been a focused research area over the years [10]. Previously, traffic signals used to be operated upon fixed cycles where each phase lasted for a specified duration irrespective of the variations in traffic congestion [11]. In modern times, traffic signals operate on varying duration cycles which collect real-time data from the roads to determine the traffic conditions and adapt to the changing requirements [12]. An aspect of interest in the research on traffic signals has been the synchronization of traffic signals to minimize traffic delays to relieve congestion [13]. Moreover, the timing of traffic signals and the need to retime the signal durations have become more important in recent years [14]. Traffic lights affect the queue lengths at the intersection and introduce delays in traffic flow [15]. Modeling and simulation of traffic signals in urban and semi-urban areas are imperative to the development of traffic engineering [16].

There have been advancements in the way how traffic signals are operated. Some new methods include the use of real-time density-based traffic control systems [17], microcontrollers [18], IoT-based signals [19], radio frequency channels for emergency vehicles [20], smart control systems [21], embedded systems [22], etc. On the other hand, roundabouts have also constantly been a topic of debate among the research community, and the choice between traffic lights and roundabouts presents an interesting perspective to research in traffic engineering and optimization. The characteristics of traffic flow at a roundabout [23] are completely different from that at a traffic signal or non-signalized intersection mainly due to the yield property and lane markings.

III. Case Study

A. Methods of traffic data collecting

Traffic data collection is the first step in the analysis of the traffic situation at a junction. In this paper, the traffic data of the T-intersection under investigation, called the Millerjord intersection, was collected primarily in two ways. The first is the manual counting of cars, which involves multiple observers physically going to the junction and counting cars for a specified duration. This step needs to be repeated multiple times on different days and at different times to get a clear picture of the traffic condition. The second method is to use the traffic data collected by the Norwegian Public Roads Administration.

1) Manual counting: For this method, data were obtained on multiple times and periods. Two sets of data are given in Figure 1. The observation is made for a duration of one hour each time, which allows easy data processing due to inherent normalization in the process. The two events represent peak traffic congestion at the junction, where event 1 shows the midweek peak and event 2 shows the overall weekly peak congestion. For this study, event 2 is of prime interest since it represents the worst-case scenario for traffic at the intersection. In Fig. 1, the probabilities of cars moving in certain directions are also calculated, which are necessary to build the simulation model in AnyLogic. At each intersection, the movement of a car depends on the probabilities introduced into the model, and it is an important step to replicate the actual traffic flow. For instance, approximately 27% of the cars coming from Narvik towards the intersection will turn right and move to the nearby shops.

		Event 1		Event 2		Average	
		Wednesday 3-4pm		Friday 3-4pm			
From	To	Tally	Probability	Tally	Probability	Tally	Probability
Narvik	Shops	192	0.271	240	0.299	216	0.286
	Hakvik	516	0.729	564	0.701	540	0.714
Shops	Narvik	104	0.433	136	0.453	120	0.444
	Hakvik	136	0.567	164	0.547	150	0.556
Hakvik	Shops	28	0.121	72	0.161	50	0.147
	Narvik	204	0.879	376	0.839	290	0.853
	Sum	1180		1552		1366	

Fig. 1. Results of the manual counting at the Millerjord intersection.

2) Online database: The second method involves using the traffic data collected and made available by the Norwegian Public Roads Administration [4]. The institute utilizes physical infrastructure installed by the roadside to count motor vehicles. Mainly, inductive loops are installed on the roads, which measure the length of the vehicle, speed, lane, direction, and vehicle category, as well as the distance between two vehicles. All the data is synchronized in real-time to the traffic data system, which is made available after three hours. The data is registered for 24 hours a day and for all days of the year. For the Millerjord intersection, the traffic data is available from 2016 to date. The details of the data acquisition process, quality of the data, and calculation methodology are discussed in detail on the Norwegian Public Roads Administration portal [24].

B. Using the traffic data

The next step is to use the collected traffic data to simulate the current state of the junction. For this purpose, AnyLogic is used, and the traffic data for the cars originating from different directions and roads are modeled in the simulation. AnyLogic uses Poisson distribution to model the flow, specifically the arrival of traffic in a road network. There has been extensive research regarding the use of Poisson distribution to model the traffic flow [6], [25]. AnyLogic uses the Djikstra algorithm to model the traffic flow [26]. The Road Traffic Library in AnyLogic contains the tools required to build a fully functional model of the intersection in a virtual environment. The traffic data obtained by the two methods were used to populate the virtual model with traffic that replicates the real traffic conditions.

IV. Model Assumptions

An assumption was made to model the traffic flow towards the intersection after the car passes the traffic counter, e.g., more than 90% of the cars that pass the traffic counter, also go through the intersection under study. In such a way, the traffic count acquired from the traffic counter could be used by assuming a division of traffic flow as it approached the intersection. This assumption was also tested on every manual instant of observation, and it was verified that on all occasions, more than 90% of cars that went through the traffic counter, proceeded to pass through the

Millerjord intersection. This assumption allows the simplification of traffic flow and permits the use of data from the traffic counter with a high level of confidence. Fig. 2 depicts this assumption.

There were only two instances of bus arrivals every hour during working hours and only one per hour after that, as compared to around 1200 instances of cars passing through the junction in one hour (buses represent 0.16% of the total traffic flow). No pedestrians were recorded moving across the pedestrian crossings on multiple manual counting visits, which indicates a negligible factor in the net calculations. Thus, the integration of pedestrian crossing in the simulation model is not taken into account in our paper.

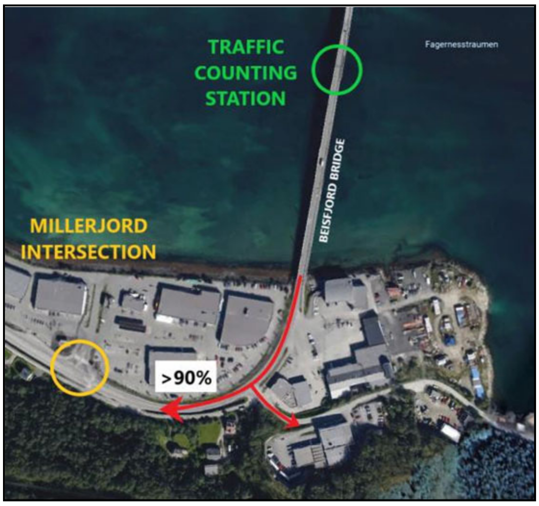


Fig. 2. Assumption of traffic flow past the traffic counter.

V. SIMULATIONS

A. Simulating the current state

The simulation model of the current state of the T-intersection is built in AnyLogic using a satellite image to exactly replicate the intersection virtually, see Fig. 3.

Fig. 3. Satellite image of Millerjord intersection.

B. Validation of model

It is important to verify and validate the model to check if the virtual model replicates the actual traffic conditions. The results obtained by the simulation model show that the traffic count, the average waiting times, and the average time used to move through the road network under study resemble closely the actual situation. Hence, the applicability of the simulation model can be validated. Fig. 4 shows a histogram that accurately represents the situation of the traffic observed first-hand at the intersection.

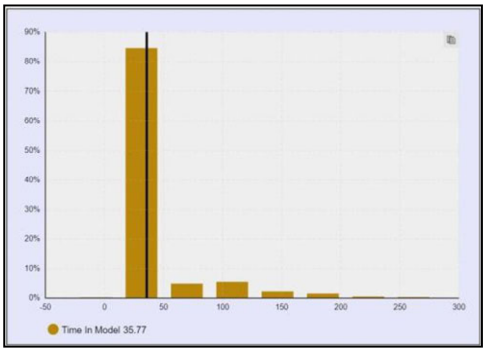


Fig. 4. Mean travel times for cars to move through the road network.

The simulation gives an average time in the model of 35.77 seconds, which is close to the actual average waiting times measured at the intersection. Moreover, the number of cars counted manually at the intersection is close to the simulation results. Then, different alternatives to relieve traffic congestion are compared, which helps to determine the best solution for the case study.

C. Alternative I - Installation of basic traffic signals

In this step, the current state of the intersection is modified by installing traffic lights. AnyLogic provides the option to use two types of traffic lights.

1) Intersection stop lines: This type stops the flow of all traffic in all lanes of a road. This is not appropriate for our model since the single-lane road coming from Hakvik towards the intersection becomes two lanes as it approaches the intersection and the traffic flows in both lanes are mutually independent.

2) Intersection lane connectors: This type of traffic signal is more suitable for the intersection under study since it allows independent control of traffic in each lane. Hence, this type of control is used in the model.

Fig. 5 shows the two states of the traffic lights of the second category used in the virtual model. The transition from state A to state B is through a 5-second time window where all signals turn yellow.

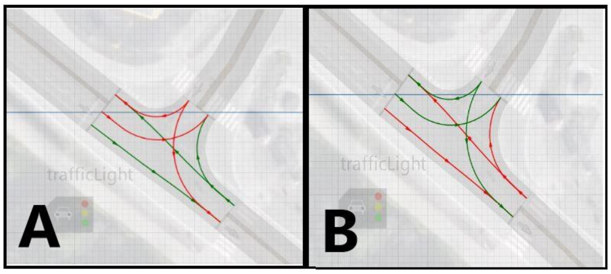


Fig. 5. Two states of the traffic signal.

Fig. 6 shows the durations used for the initial traffic signal in the model, which is generated based on general observation of the traffic flow.

Fig. 6. Durations of traffic lights in the initial model.

D. Alternative II - Installation of optimized traffic signals

The optimization of traffic lights relates to finding the optimal open/close duration for each lane depending on the traffic congestion in the particular lane. For this purpose, the fixed duration signals are replaced by variables in the model and then solved for a minimization problem in AnyLogic. The following Fig. 7 shows the configuration of variables used for the optimization process.

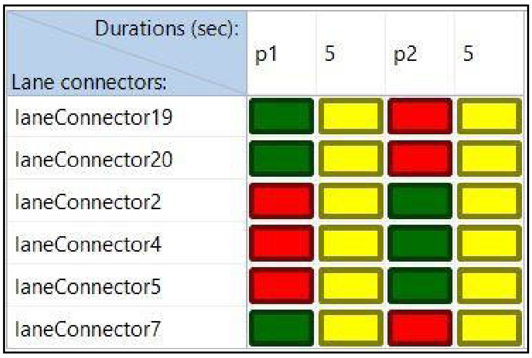
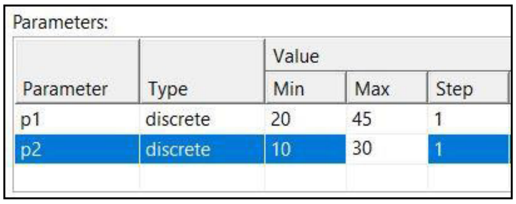


Fig. 7. Configuration of variables used for the optimization.

Fig. 8 shows the parameters used in the optimization in AnyLogic.



Parameters:

Parameter	Type	Value Min	Max	Step
p1	discrete	20	45	1
p2	discrete	10	30	1

Fig. 8. Parameters used for the optimization.

The objective function of the minimization process is the mean travel time of cars through the road network and the two variables $p1$ and $p2$ are the two states of the traffic signal at the intersection.

E. Alternative III - Installation of a roundabout

The second alternative is the installation of a roundabout at the T-intersection. In certain situations, roundabouts have been used to reduce overall traffic congestion. However, due to their inherent property of the necessity for drivers to reduce speed when navigating through a roundabout, it sometimes results in higher net congestion, although stationary waiting times may be reduced.

To simulate a roundabout in AnyLogic, the only way is to connect individual roads one by one through intersections and adjust the size, shape, and orientation of each section of the road so that the overall network can resemble a roundabout. Two important properties of a roundabout are yield-at-entry and lane discipline. Care was taken to ensure these characteristics in the model by connecting lanes in an appropriate manner, and activating yield property at relevant stop lines at entry points of the roundabout. Fig. 9 shows the roundabout in the model, and a partially transparent traffic density map is also mapped onto it.

Fig. 9. A model of the roundabout with traffic density mapped

VI. RESULTS

A. Current state model

As shown in Fig. 10 and 11, the data obtained from the simulation shows that a large percentage of cars, about 84%, take less than 50 seconds to pass through the road network, which gives a mean travel time of 35.77 seconds. However, this high percentage of apparently good traffic flow shadows the fact that about 10% of the cars take two minutes or more to pass through the road network, and more than 50% of this 10 percent comprised of the cars coming out of the shops and onto the main road, and this particularly is the traffic congestion problem under study in this paper. This situation was also observed on multiple occasions when manual counting was done at the Millerjord intersection.

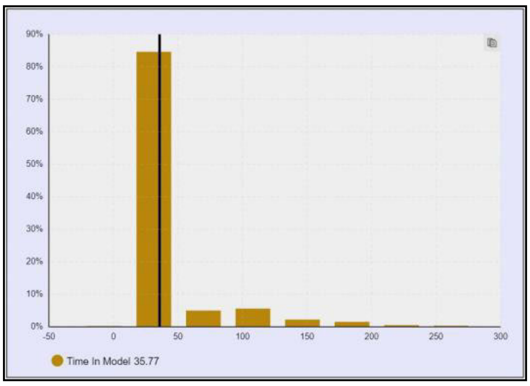


Fig. 10. Histogram of current state model.

timeInModel

Count	1,312		
Mean	35.765		
Min	12.089		
Max	265.444		
Deviation		38.666	
Mean confidence		2.092	
Sum	46,923.772		
From	To	PDF(hits)	CDF(cum hits)
-26.3	12.1	3	3
12.1	50.5	1,110	1,113
50.5	88.9	66	1,179
88.9	127.3	73	1,252
127.3	165.7	29	1,281
165.7	204.1	20	1,301
204.1	242.5	7	1,308
242.5	280.9	4	1,312

Fig. 11. Simulation results showing the travel time of cars across the current state road network.

B. Basic traffic signals

The simulation of the road network with basic traffic lights based on the fixed duration of signals shows interesting results. Fig. 12 illustrates that nearly 70% of the cars take less than 50 seconds to pass through the network and cumulatively about 90% of the cars take 80 seconds or less to move through the network. However, about 8% of the cars face a situation where they had to wait for two minutes or longer to move through the network. Moreover, the cars coming out of the shops and onto the main road still face long waiting times and the queuing problem.

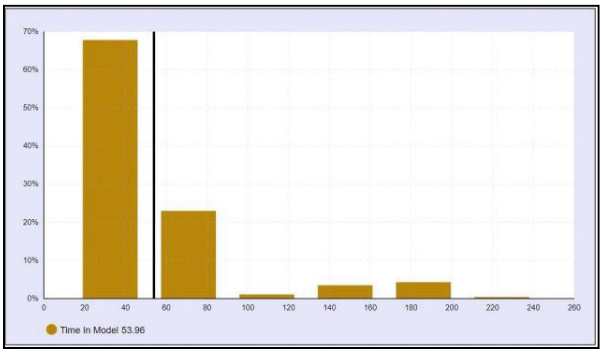


Fig. 12. Histogram of road network with basic traffic lights

timeInModel

Count	1,136		
Mean	53.961		
Min	14.524		
Max	209.868		
Deviation		39.383	
Mean confidence		2.29	
Sum	61,300.176		
From	To	PDF(hits)	CDF(cum hits)
13.3	51.7	770	770
51.7	90.1	261	1,031
90.1	128.5	12	1,043
128.5	166.9	40	1,083
166.9	205.3	49	1,132
205.3	243.7	4	1,136

Figure 13: Simulation results showing the travel time of cars across the road network with basic traffic lights

The simulation results in Fig. 13 show that the mean travel time for cars moving through the road network rise by 50% to 53.96 seconds. This is due to the fixed nature of the traffic signals which disregard any changes in the arrival rates of cars. Moreover, only approximately 67% of the cars pass through the network within 50 seconds.

C. Optimized traffic signals

After running the minimization algorithm on the traffic lights setups, the durations of red/green cycles of the traffic lights are changed, and the results of the optimization (minimization of mean travel time) are shown in Fig. 14.

	Current	Best
Iterations completed:	504	180
Objective: ↓	34.581	25.588
Parameters		Copy best
p1	32	34
p2	24	10

Fig. 14. Results of traffic lights optimization

As shown in Fig. 14, the best iteration resulted in a mean travel time of 25.588 seconds, whereas the optimal durations for the two traffic light phases were found to be 34 seconds and 10 seconds, respectively.

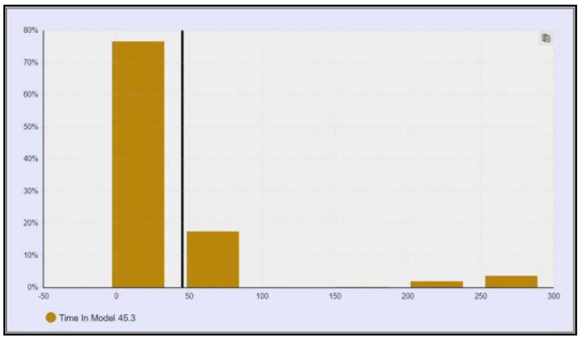


Fig. 15. Histogram of road network with optimized traffic lights

Using these values in the model, Fig. 15 shows that nearly 80% of the cars can pass through the network within 40 seconds. Fig. 16 shows the simulation results with the optimized traffic signal.

timeInModel

Count	1,177		
Mean	45.302		
Min	14.548		
Max	291.172		
Deviation		51.995	
Mean confidence		2.971	
Sum	53,319.985		
From	To	PDF(hits)	CDF(cum hits)
-10.6	40.6	901	901
40.6	91.8	206	1,107
91.8	143	1	1,108
143	194.2	2	1,110
194.2	245.4	23	1,133
245.4	296.6	44	1,177

Fig. 16. Simulation results showing reduced travel times of cars across the road network with optimized traffic lights

Fig. 16 shows that the mean travel time for all cars is reduced by approximately 16% from 53.9 seconds to 45.3 seconds, Meanwhile, the percentage of cars that have a travel time of more than one minute has been significantly reduced. However, in this case, about 5% of the cars have a travel time of more than 3 minutes.

D. Road network with roundabout

Another alternative solution is the use of a roundabout at the intersection. AnyLogic does not have a built-in roundabout element in the Road Traffic Library, so it must be made by connecting roads in a particular manner manually. Fig. 9 shows the roundabout constructed in our experiment. Fig. 17 shows the histogram obtained from the simulation, which reveals that about 80% of the cars pass through the network in less than 50 seconds. Furthermore, about 90% of the cars pass through the network in less than 90 seconds.

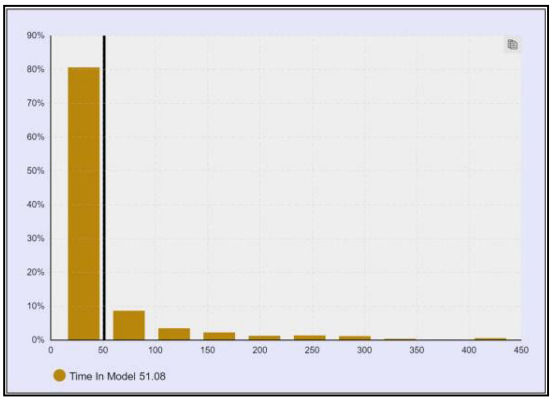


Fig. 17. Histogram showing travel times for cars passing through a road network with a roundabout.

timeInModel

Count	1,066		
Mean	51.084		
Min	14.857		
Max	430.2		
Deviation		60.262	
Mean confidence		3.618	
Sum	54,455.171		
From	To	PDF(hits)	CDF(cum hits)
10	53.2	859	859
53.2	96.4	93	952
96.4	139.6	37	989
139.6	182.8	24	1,013
182.8	226	14	1,027
226	269.2	15	1,042
269.2	312.4	13	1,055
312.4	355.6	4	1,059
355.6	398.8	1	1,060
398.8	442	6	1,066

Fig. 18. Simulation results showing the travel times of cars across the road network with a roundabout.

Fig. 18 shows that about 80% of the cars pass through the road network within 50 seconds, while about 5% of the vehicles had a travel time of 3 minutes or more, and about 2% of the vehicles had a travel time of more than 5 minutes.

VII. Discussion

The alternative solutions discussed and compared in this paper do not show a clear option that outperforms the others in all dimensions. The factor is that perhaps the most significant influencing factor of the traffic congestion at the Millerjord intersection is the very high traffic volume, which causes long waiting times for cars originating from the shops and reduces the arrival spacing of vehicles. For fixed-duration traffic lights, the mean travel time is the longest. The second alternative with the optimized traffic lights significantly improves the traffic flow compared to the use of basic traffic lights, which allow the highest percentage of cars to pass through the intersection in the shortest time window. The third alternative of using a roundabout yields a result similar to the second alternative, but the very low arrival spacing causes the roundabout to choke occasionally, which leads to significantly reduced mean speeds and long travel times for some vehicles.

One important factor in mean travel time determination is that this unit comprises two parts. One is the fixed travel time based on travel at maximum permissible speed across the road network if there were no other vehicles to cause any congestion, and the other is the variable part of travel time which depends on the traffic congestion and road conditions in the road network at a given time. For the road network discussed in this paper, the length of the network is 300 meters from end to end. For cars traveling at a maximum permissible speed of 60kph, the travel time across the network is 18 seconds. It is noteworthy that the alternatives discussed affect the second part, e.g., the variable part of the travel time while the first part (18s) remains constant.

VIII. Conclusion

This paper solves a real-world traffic congestion problem at a T-intersection in Narvik, Norway. With the help of AnyLogic simulation, several alternative solutions to the traffic congestion problem are tested and compared. In our experiment, the second alternative based on optimized traffic lights shows a promising solution for the queuing problem as it allows more than 80% of vehicles to pass through the network within 40 seconds. The results show that it is a better alternative than the basic traffic lights due to significant improvement in mean travel time. Besides, it is a better alternative than a roundabout, because roundabouts tend to choke under such congested traffic conditions and present a high risk of accidents due to very less spacing between cars and the inherent rules of travel through a roundabout. Furthermore, this alternative can be further improved by installing smart sensors to change the signal duration based on real-time traffic congestion conditions. Moreover, reducing traffic congestion at busy intersections can significantly reduce CO_2 emissions and improve the surrounding air quality.

Acknowledgment

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