TRAFFIC CONTROL ANALYSIS: ROUNDABOUTS VS. SIGNALIZED INTERSECTIONS

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ABSTRACT. In this paper, we studied different traffic control systems and their effects on traffic flow dynamics. Essentially, our focus was on roundabouts and signalized intersections with traffic lights. Although there are many variables effecting both of the systems, we completed our comparison by focusing on the effects of vehicle density and traffic light timings. We provided detailed descriptions of them and utilized Python to code and run simulations for comparison. Since this topic has been of great interest and significance for urban planning, many researchers, traffic agencies, and government bodies have conducted respective studies on it. However, traffic flow is inherently stochastic, making any studies on it complicated and difficult. Therefore, we aimed to propose a simplified and accessible way to understand these intricate dynamics, while acknowledging existing constraints.

Keywords: Traffic simulation, Roundabouts, Signalized intersections, Traffic light timings, Vehicle density, Traffic control systems, Traffic flow analysis

CONTENTS

1. Introduction

Defined as "the vehicles that are on a road at a particular time" by the *Oxford English Dictionary*, the concept of traffic, in the context of transportation, has been around in various forms for centuries. From using camels in deserts to horse-drawn carriages to cars, humans have adapted to different means of transportation aligning with the accessibility and level of development and innovation of the time that they were living in.

1.1. Problem Definition.

As the human societies progressed, technological innovations and societal rules developed and improved interrelatedly as well. These developments and improvements can be observed through the development of traffic. The development of traffic is attributable to a couple of factors, including urbanization, the development of transportation infrastructure, the surge in the number of registered cars, population growth, and the need for efficient and fast transportation systems. According to the survey conducted by the *U.S. Department of Transportation Federal Highway Administration*, the number of cars registered in the United States between the years 1990-2021 mostly followed a positive trend [23]. That is, in 1990, the number of cars registered in the United States was 193,057,380, while this number increased to 282,366,290 by 2021. The histogram prepared by the *Statista Research Department* illustrates this change in detail [6]:

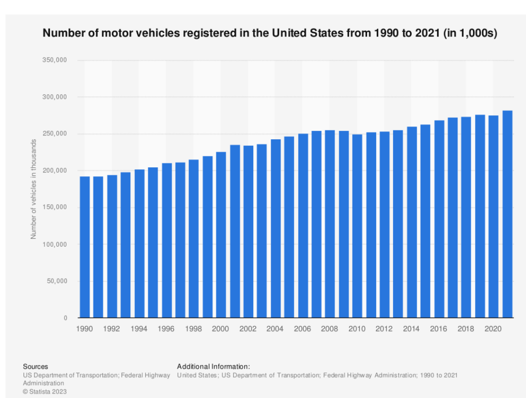

Figure 1. Number of motor vehicles registered in the United States from 1990 to 2021; Credit: Statista

This increase in the number of cars registered resulted in the excessive occurrence of traffic congestions, traffic jams, and traffic accidents. According to data collected and shared by *Global Traffic Scorecard by INRIX*, the total number of hours spent in the traffic due to traffic congestion in London was the highest in global with 156 hours in 2022 [12]. This was followed by Chicago IL with 155 hours and Paris with 138 hours. Moreover, on average, the United Kingdom spent 80 hours in traffic due to traffic congestion in 2022, which is a 7 hour increase from the previous year [12]. On the other hand, the United States spent 51 hours in traffic due to traffic congestion in 2022, which is a 15 hour increase from the previous year. Although this increase can be partially attributed to the annulment of rules and temporary laws implemented because of the COVID-19 pandemic, the economic costs of these congestions are non-negligible. In 2022, a typical commute cost $926 in the United Kingdom on average, which followed an increase of $147 compared to previous year. Likewise, in 2022, a typical commute cost $869 in the United States on average, which followed an increase of $305 compared to previous year. One another significant example to effects of traffic problems was observed in People's Republic of China on the Beijing-Tibet Expressway. Started to form on 14$^{\text{th}}$ August 2010 and named as the biggest traffic jam in the world, this traffic jam lasted for approximately 12 days and stretched over 100 kilometers.

Figure 2. The Beijing-Tibet Expressway traffic jam in China in August 2010; Credit: Earthly Mission

In order to combat these traffic problems, government authorities and transportation agencies have come up with various different policies and implementations. Two of them are roundabouts and signalized intersections with traffic lights, which we will investigate and compare in this paper.

Defined as "a place where two or more roads meet, forming a circle that all traffic must go around in the same direction" by *Oxford English Dictionary*, roundabouts are a type of circular junctions. In roundabouts, vehicles move counterclockwise around a central island. Drivers yield to those already in the circle, promoting smooth traffic flow.

Figure 3. Roundabout; Credit: JamesBrey / Getty Images

The first emergence of roundabouts can be traced back to 1790s, to the designs of American-French architecture and engineer *Pierre Charles L'Enfant* [24]. His roundabout designs were not like modern roundabouts, which were introduced in 1960s, but they shared a couple of similarities, such as utilizing circular traffic flow and being a part of circular joints.

Although roundabouts first emerged in the United States, in 2014, there were 1118 intersections per a roundabout in the United States, while this ratio was 45 intersections per a roundabout in France [18]. A couple of reasons can be attributed to this difference in ratios, such as inefficient and late implementation of early roundabouts, different driving culture, and a widespread population in the United States [22]. Furthermore, the United States is not the only country experiencing a hardship in converting and adapting to roundabouts; with similar reasons, countries such as Japan, Canada, and the Republic of South Africa have experienced the same issue as well. In these countries, instead of roundabouts, government authorities and transportation agencies preferred to implement and utilize signalized intersections with traffic lights.

Defined as "a signal that controls the traffic on a road, by means of red, yellow, and green lights that show when you must stop and when you can go" by *Oxford English Dictionary*, traffic lights are an indispensable and pivotal component of modern urban traffic management systems. At traffic lights vehicles stop or proceed based on the color of the lights. When the light is green, drivers can move. When it turns yellow, they should prepare to stop. And when it turns red, they must come to a complete stop. This system controls the orderly flow of vehicles at intersections.

Figure 4. Signalized intersection with traffic light; Credit: Snyder & Associates

Although far from its modern shape and system, the first traffic lights were introduced in 1868 at *Parliament Square* in London [31]. However, this attempt failed and turned into a disaster when the traffic light exploded and killed the police officer who was working the signs [31]. Government organizations and road engineers had to wait for electricity usage to become widespread in the world. In 1912, American policeman *Lester Wire* had devised the first electric traffic light in Salt Lake City, Utah. From that point, many engineers improved on his model, and countries systematically converted and adapted to traffic lights and the traffic regulations such a conversion and adaptation needed [17].

As stated earlier, the United States has a preference toward signalized intersections with traffic lights compared to roundabouts. In the United States, as of August 2018, there were 6,302,865 intersections for the 497 urbanized areas [5]. Approximately 360,000 of these intersections were signalized intersections operated by more than 15,000 city, county, and state traffic agencies [7]. This was an increase of approximately 95,000 signalized intersections than the number reported by the *Institute of Transportation Engineers* in 2004 [4]. This same pattern of increment in the number of signalized intersections can be observed not only in the United States but also in countries such as Japan and France, which is historically more inclined to implement roundabouts than signalized intersections with traffic lights as evidenced by France's position of having the most roundabouts in the world [13].

As much as they are one of the most used traffic control strategies, similar to roundabouts, traffic lights also brought economic burden to countries and, at times, resulted in significant time inefficiencies for drivers. According to an *United Kingdom Institute of Economic Affairs* report authored by *Martin Cassini* and *Dr. Richard Wellings*, then-head of transport, the number of traffic lights has increased by 25% since 2000, surpassing the 5% increase in the number of registered vehicles during the same period [29]. This disproportionate increase has shown that a two-minute delay to each car journey results in an annual loss of around £16 billion, equivalent to 1% of the United Kingdom GDP [29]. Many methods have been proposed and implemented to solve the problem. However, even one of the most suggested methods, traffic signal re-timing, comes with an average cost of $1,500 to $2,500 per signalized intersection [14]. Although this method is proved to be cost-efficient and relatively inexpensive compared to other method, it still needs a well-preserved city budget.

In summary, the main problem concerning roundabouts and signalized intersections with traffic lights is accurately and efficiently deciding which one is more appropriate to implement in a certain location by considering factors such as traffic light timing, density of registered vehicles, and other variables that are unpredictable and extraordinary events, such as accidents.

1.2. **Literature Review.** Many researchers, engineers, government organizations, and transportation agencies have been investigating and comparing roundabouts and signalized intersections. Their main concerns regarding this investigation and comparison are determining which traffic control strategy is safer, and more time- and cost-efficient.

For roundabouts, Retting et al. (2006) showed that traffic congestion, as measured by the vehicle-to-capacity ratio, was reduced by 58-84% [25]. These results provide further evidence that roundabouts can improve traffic flow and public support for roundabouts increases after they are in place. For the safety of roundabouts, Gross et al. (2013) conducted an analysis and substantiated that roundabouts have the potential to significantly reduce crashes and severity of these crashes [10]. According to Retting et al. (2001), roundabouts can significantly reduce all crash severities by 38% and all injury crashes by 76%, making them an effective safety treatment for intersections, with a focus on the United States for their study [26]. To improve the safety at roundabouts, by reviewing past crash reports and visiting several roundabouts, Mandavilli et al. (2009) established that roundabout safety can be improved by adding design features such as entry deflection on approach roads, larger 'roundabout ahead' and 'yield' signs, enhanced landscaping of central islands, reflective pavement markers, and 'yield' signs at the entrance to roundabouts [15]. Moreover, Al-Marafi et al. (2020) conducted a study with similar objectives and further corroborated that increasing the number of entry lanes, entry width, entry radius, traffic volume, circulatory roadway width, weaving width, and speed limit have positive effects on roundabout safety [2]. However, a different study by Ahn et al. (2009) demonstrated that roundabouts provide efficient movement of vehicles when the approach traffic volumes are relatively low for their case study [1]. Their finding has been consistent with other studies we will discuss in the later parts of this paper.

For signalized intersections with traffic lights, Zaji et al. (2023) showed that, based on their results, in contrast to uncontrolled intersections without traffic lights, optimized traffic lights can significantly contribute to total travel time-saving [33]. To increase this travel time-saving, Li et al. (2018) conducted a different study and proposed a traffic control strategy which established that connected and automated vehicles can use traffic light information to optimize their velocity profiles and reduce idling at red lights, resulting in a 19.2% decrease in total trip time and an 18.1% decrease in fuel consumption [11]. Without proposing any traffic control strategy, Gershenson (2004) validated that just by using simple rules and no direct communication, traffic lights are able to self-organize and adapt to changing traffic conditions, reducing waiting times, number of stopped cars, and increasing average speeds [9]. Likewise, without also proposing any traffic control strategy, Olaverri-Monreal et al. (2018) put forward that their study's results show an increase in driving efficiency in the form of improvement of traffic flow, reduced gas emissions, and waiting time at traffic lights after the drivers adjusted their velocity to the speed calculated by the Traffic Light Assistance (TLA) system [21]. For the safety of signalized intersections with traffic lights, Yannis et al. (2013) demonstrated that nighttime lighting has great potential in improving traffic safety and reducing the accident severity, particulary for pedestritians and drivers killed and seriously injured [32]. However, another study by Uttley et al. (2017) had contradictory results which suggested that there is a significantly greater risk of a pedestrian road traffic collision at a crossing after-dark than during daylight, and while 98% of these crossings are lit by road lighting, this raises questions about the adequacy and effectiveness of the lighting used [30]. By this extent, Rudin-Brown et al. (2012) took a different direction with their study and asserted that the installation of traffic lights at real-world level crossings would not be likely to offer safety benefits over and above those provided already by flashing lights with boom barriers [27].

For investigating and comparing roundabouts and signalized intersections with traffic lights, Zhou et al. (2022) argued that roundabouts have a higher capability of vehicle passing than intersections, especially for a large traffic volume [34]. Correlatively, Oh et al. (2000) conducted a study and showed that roundabouts provide more capacity than signalized intersections with traffic lights for approaching traffic of up to 1,000 vehicles per hour per direction [20]. On the other hand, five years later, Bared et al. (2005) published their study, and by utilizing a traffic simulation software, they found that roundabouts perform similarly to signalized intersections with traffic lights in terms of average delay when operating below capacity, but signalized intersections perform slightly better at heavy volumes when roundabouts are operating at capacity [3]. This contradiction raised an important question among researchers about a possible replacement of roundabouts and signalized intersections with traffic lights based on each location's unique needs and external variables. However, Daniels et al. (2008) confirmed that roundabouts that replace traffic signals perform worse when compared to roundabouts at other types of intersections most of the time [8]. For instance, according to Estévez Mauriz et al. (2018), when a roundabout becomes unbalanced and subsequently leads to a traffic congestion, the roundabout can become noisier than a signalised crossing at signalized intersections with traffic lights [16]. For comparing the safety of roundabouts to signalized intersections with traffic lights, Nambisan et al. (2007) conducted a study, and although high volume intersections with signalized traffic controls appeared to be safer than the corresponding candidate roundabouts in their study, the results were not found to be statistically significant [19]. Conversely, Saccomanno et al. (2008) demonstrated that roundabouts yield reduced exposure times to rear-end conflicts compared with signalized intersections [28].

In conclusion, some studies suggest that roundabouts provide more capacity and reduced exposure times to rear-end conflicts compared to signalized intersections with traffic lights, especially for lower traffic volumes, while other studies show that signalized intersections perform better at heavy volumes, have shorter optimal cycle lengths, and produce lower NO_x emissions.

1.3. **Objective of the Paper.** While numerous studies have investigated the merits and drawbacks of roundabouts and signalized intersections, a noticeable gap persists in the research landscape—a comprehensive comparison of these two traffic control systems that considers dynamic variables, such as traffic light timing, vehicle density, and the impact of unpredictable events like accidents.

This research paper aims to conduct rigorous simulations and analyses to comprehensively compare and investigate the performance of roundabouts and signalized intersections with traffic lights. Our primary focus is on providing practical insights into the selection of appropriate traffic control systems for diverse contexts.

Through Python-based simulations, we will examine the impact of traffic light timing and vehicle density on system efficiency and traffic flow within roundabouts and signalized intersections. By manipulating these variables, we intend to assess the speed and efficiency of both control systems under varying conditions.

The core objective of this paper is to use simulations to:

(1) Evaluate the speed and efficiency of roundabouts and signalized intersections under different traffic light timings.
(2) Analyze how changes in vehicle density influence the safety and traffic speed of these control systems.
(3) Provide empirical evidence to aid in the decision-making process for selecting the most suitable traffic control system for specific traffic scenarios.

In summary, this study will employ Python-based simulations as a mathematical tool to directly compare the performance of roundabouts and signalized intersections. The mathematical approach in this paper focuses on practical assessments, and the results will contribute to informed decision-making in transportation planning and infrastructure development.

2. Methodology

In this paper, we primarily utilized Python to write the codes for two different simulations: 'roundabout' simulation and 'signalized intersection' simulation. These two simulations are inspired from real-life scenarios to enhance the articulacy and comprehensibility of the paper and study for the readers.

2.1. Simulation Setup.

In this subsection, we introduced and detailed the simulations that we used for our study. Both of the simulations follow similar structures with varying initial conditions, rules, and parameters. These simulations are integral to our research and enable a detailed evaluation of traffic control systems in diverse scenarios.

2.1.1. *Roundabout Simulation.*

In this part, we emulate the dynamics of vehicles within a roundabout. This simulation allows us to explore how different factors affect the efficiency and speediness of roundabouts, offering insights into their performance under varying conditions.

2.1.1.1. *Initial Conditions.*

The roundabout simulation is designed to simulate the behavior of vehicles within a roundabout traffic control system. We initialized the simulation with the following parameters:

```python
x_cars = [8, 9, 10] # Initial positions of X Car 1 - X Car 2 - X Car 3 along
↪ the X-axis
```

```python
y_cars = [8, 9, 10] # Initial positions of Y Car 1 - Y Car 2 - Y Car 3 along
↪ the Y-axis
```

```python
iteration_count = 0 # Variable to count the total number of iterations
```

Then, we defined these initial conditions:

(1) The cars are assumed to have no velocity and acceleration.
(2) The roundabout has a radius of 1 and center at (0,0).
(3) All cars will be of the same type.
(4) All cars will accommodate 1 passenger.

(5) The driver behavior, such as reaction times or following distances, will be the same for all cars.
(6) Traffic-flow models are meant to describe normal conditions, while accidents are almost always caused by exceptional driving mistakes that are not part of normal driving behavior and thus not part of the intended scope of the model.

Therefore, our simulation initially will look like this:

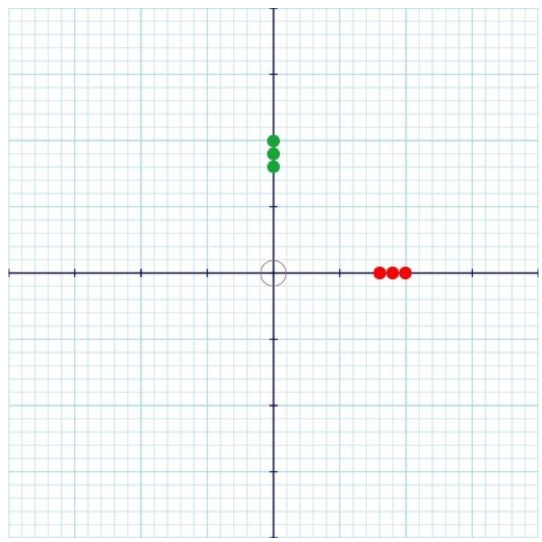

Figure 5. Initial roundabout simulation

in which red dots represent the X cars, green dots represent the Y cars, and brown circle represents the roundabout.

2.1.1.2. *Rules*. After setting the parameters and initial conditions, we defined these rules:

(1) There could be only one car in the roundabout at a time.
(2) Cars on positive X axis moves toward negative X axis.
(3) Cars on positive Y axis moves toward negative Y axis.
(4) It is assumed that there are no traffic lights, stop signs, lane changing, collision avoidance, and disrupting conditions such as wet ground.
(5) None of the cars will pass each other, and all of them will move in a queue-like way by being 1-unit apart.
(6) As defined specifically, iterations will be used to keep track of how many cycles or loops are required to complete the simulations with specific variables.
(7) The simulation will end when the last car is at either the point $(-10, 0)$ or $(0, -10)$ depending on its starting location.

After defining these rules, we also coded conditions on Python for two other important rules:

```
if not (x_cars[x] - 1) in x_cars: # Making sure that there are no cars at the left of X cars
    if x_cars[x] == 1 and 0 in y_cars: # If the current X car is at 1 and Y cars are at 0, X cars will not move left by one unit
```

```
        continue
    x_cars[x] = x_cars[x] - 1 # The current X Car is moving left by one unit
```

```
if not (y_cars[y] - 1) in y_cars: #Making sure that there are no cars at the
↪  down of Y cars
    if y_cars[y] == 1 and 0 in x_cars: # If the current Y car is at 1 and X
    ↪  cars are at 0, Y cars will not move down by one unit
        continue
    y_cars[y] = y_cars[y] - 1 # The current Y Car is moving down by one unit
```

2.1.2. ***Signalized Intersection Simulation***. In this part, we replicate the vehicle interactions at a conventional signalized intersection controlled by traffic lights. By manipulating parameters such as traffic light timings and vehicle density, this simulation enables us to analyze the behavior and performance of signalized intersections. It serves as a vital component in our comparative study of traffic control systems.

2.1.2.1. *Initial Conditions*. As stated previously, the simulations for both roundabouts and signalized intersections follow similar structures with varying parameters and initial conditions. All initial conditions stated with codes for roundabout simulation apply for signalized intersection simulation with the addition of this condition:

```
traffic_light = 0 # 0 is Red in X direction and 1 is Red in Y direction
```

All initial conditions stated in a numbered list for roundabout simulation apply for this simulation except for the initial condition for roundabout shape, which is labeled as 2. Moreover, we define another condition:

(1) The traffic lights are located at points $(1, 0)$ and $(0, 1)$.

Therefore, our simulation initially will look like this:

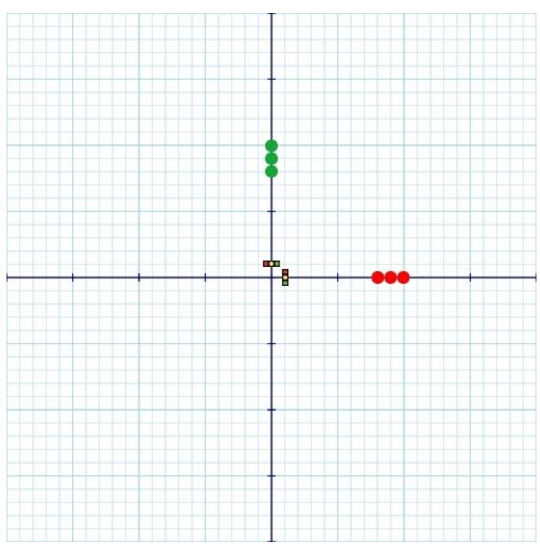

Figure 6. Initial signalized intersection simulation

in which red dots represent the X cars, green dots represent the Y cars, and traffic light figures represent the actual traffic lights.

2.1.2.2. *Rules*. All the defined rules in the numbered list for roundabout simulation will also apply for signalized intersection simulation except for the rule for car behavior in the roundabout, which is labeled as 1. Moreover, these additional rules are defined specifically for this simulation:

(1) If the traffic light is red, the cars cannot move.
(2) If the traffic light is green, the cars can move.
(3) If the traffic light is yellow, it will be assumed that it does not have any affect on the simulation; thus, it will not be considered.

After defining these rules, we again coded conditions on Python for three other important rules:

```python
if not (x_cars[x] - 1) in x_cars: # Making sure that there are no cars at the left of X cars
    if x_cars[x] == 1 and (0 in y_cars or traffic_light == 0): # If the current X car is at 1 and either Y cars are at 0 or the traffic light is Red in X direction, X cars will not move left by one unit
        continue
    x_cars[x] = x_cars[x] - 1 # The current X Car is moving left by one unit
```

```python
if not (y_cars[y] - 1) in y_cars: # Making sure that there are no cars at the down of Y cars
    if y_cars[y] == 1 and (0 in x_cars or traffic_light == 1): # If the current Y car is at 1 and either X cars are at 0 or the traffic light is Red in Y direction, Y cars will not move down by one unit
        continue
    y_cars[y] = y_cars[y] - 1 # The current Y Car is moving down by one unit
```

```python
if iteration_count % 10 == 0: # After each iteration, if the remainder is 0, the traffic light changes color
    print("Traffic Light is Changing", traffic_light)
    if traffic_light == 0:
        traffic_light = 1 # Changing the traffic light color
    else:
        traffic_light = 0
```

2.2. **Mathematical Insights.** Both of the simulations serve as mathematical models to evaluate the performance of roundabouts and signalized intersections with traffic lights under varying conditions. While these simulations do not involve complex mathematical equations, they still provide valuable insights into traffic flow dynamics and system efficiency. By manipulating number of cars and traffic light timings, we can observe how these factors influence traffic behavior.

2.3. **Program Implementation.** Both of the simulations are implemented using Python as the programming language. Code snippets for both the roundabout and signalized intersection simulations have been provided in their respective sections above. These code snippets are instrumental in conducting the simulations and collecting data for analysis. Moreover, complete simulation codes for both roundabout and signalized intersection simulations can be found in 9.

2.4. **Data Collection and Analysis.** As part of the simulations, we collect data on the movement of vehicles, traffic light changes, and iteration counts. Subsequently, we analyze the data to evaluate the speediness and efficiency of both roundabouts and signalized intersections with traffic lights under different conditions. In our simulations, we frequently use print function to document the results we obtain. When each simulation is concluded, in order to make inferences, we use this code to print the total number of iterations:

```
    iteration_count += 1 # Increasing the iteration count by 1 in each loop

print("Total Iterations:", iteration_count) # Printing the total number of
↪  iterations
```

3. Results

We conducted a series of simulations to investigate the impact of varying vehicle density and different traffic light timings on the efficiency and speediness of roundabouts and signalized intersections with traffic lights as stated previously in 1.3. In this section, we present the outcomes of our simulations, including changes to key variables and printout results.

3.1. **Varying Vehicle Density.** In our first set of simulations, we focused on varying the number of vehicles within the roundabout simulation and signalized intersection simulation while keeping other factors constant—for all simulations under this subsection, we set the traffic light timing to 4. This allowed us to assess the effects of vehicle density on comparing the effectiveness and speediness of both traffic controlling systems.

In the first comparison, we set the number of cars to 3 for both of the simulations:

```
x_cars = [8, 9, 10]
y_cars = [8, 9, 10]
```

After running our codes, for the roundabout simulation, we received "**Total Iterations: 23**" printout. For the signalized intersection simulation, we received "**Total Iterations: 24**" printout.

In the second comparison, we set the number of cars to 4 for both of the simulations:

```
x_cars = [7, 8, 9, 10]
y_cars = [7, 8, 9, 10]
```

After running our codes, for the roundabout simulation, we received "**Total Iterations: 24**" printout. For the signalized intersection simulation, we received "**Total Iterations: 28**" printout.

In the third comparison, we set the number of cars to 8 for both of the simulations:

```
x_cars = [3, 4, 5, 6, 7, 8, 9, 10]
y_cars = [3, 4, 5, 6, 7, 8, 9, 10]
```

After running our codes, for the roundabout simulation, we received "**Total Iterations: 28**" printout. For the signalized intersection simulation, we received "**Total Iterations: 30**" printout.

In the fourth comparison, we set the number of cars to 10 for both of the simulations:

```
x_cars = [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]
y_cars = [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]
```

After running our codes, for the roundabout simulation, we received "**Total Iterations: 30**" printout. For the signalized intersection simulation, we received "**Total Iterations: 36**" printout.

In the fifth and last comparison, we set the number of cars to 11 for both of the simulations:

```
x_cars = [0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10]
y_cars = [0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10]
```

After running our codes, for the roundabout simulation, we received "**Total Iterations: 31**" printout. For the signalized intersection simulation, we received "**Total Iterations: 36**" printout. However, after increasing the number of cars to 11, the printout results did not change for both roundabout simulation and signalized intersection simulation.

3.2. **Varying Traffic Light Timings.** In the second set of simulations, we focused on altering traffic light timings at signalized intersections to explore their impact on traffic flow and efficiency while keeping other factors constant—for all simulations under this subsection, we set the number of cars to 4. The codes and printouts below depict the behavior of vehicles at signalized intersections with varying traffic light timings and its comparison to roundabouts.

In the first comparison, we set the traffic light timing to 1 for both of the simulations:

```
if iteration_count % 1 == 0:
```

After running our codes, for the roundabout simulation, we received "**Total Iterations: 24**" printout. For the signalized intersection simulation, we received "**Total Iterations: 32**" printout.

In the second comparison, we set the traffic light timing to 2 for both of the simulations:

```
if iteration_count % 2 == 0:
```

After running our codes, for the roundabout simulation, we received "**Total Iterations: 24**" printout. For the signalized intersection simulation, we received "**Total Iterations: 28**" printout.

In the third comparison, we set the traffic light timing to 3 for both of the simulations:

```
if iteration_count % 3 == 0:
```

After running our codes, for the roundabout simulation, we received "**Total Iterations: 24**" printout. For the signalized intersection simulation, we received "**Total Iterations: 26**" printout.

In the fourth comparison, we set the traffic light timing to 4 for both of the simulations:

```
if iteration_count % 4 == 0:
```

After running our codes, for the roundabout simulation, we received "**Total Iterations: 24**" printout. For the signalized intersection simulation, we received "**Total Iterations: 28**" printout.

In the fifth comparison, we set the traffic light timing to 5 for both of the simulations:

```
if iteration_count % 5 == 0:
```

After running our codes, for the roundabout simulation, we received "**Total Iterations: 24**" printout. For the signalized intersection simulation, we received "**Total Iterations: 25**" printout.

In the sixth comparison, we set the traffic light timing to 8 for both of the simulations:

```
if iteration_count % 8 == 0:
```

After running our codes, for the roundabout simulation, we received "**Total Iterations: 24**" printout. For the signalized intersection simulation, we received "**Total Iterations: 25**" printout.

In the seventh comparison, we set the traffic light timing to 10 for both of the simulations:

```
if iteration_count % 10 == 0:
```

After running our codes, for the roundabout simulation, we received "**Total Iterations: 24**" printout. For the signalized intersection simulation, we received "**Total Iterations: 25**" printout.

In the eighth comparison, we set the traffic light timing to 11 for both of the simulations:

```
if iteration_count % 11 == 0:
```

After running our codes, for the roundabout simulation, we received "**Total Iterations: 24**" printout. For the signalized intersection simulation, we received "**Total Iterations: 26**" printout.

In the ninth comparison, we set the traffic light timing to 50 for both of the simulations:

```
if iteration_count % 50 == 0:
```

After running our codes, for the roundabout simulation, we received "**Total Iterations: 24**" printout. For the signalized intersection simulation, we received "**Total Iterations: 65**" printout.

In the tenth and last comparison, we set the traffic light timing to 100 for both of the simulations:

```
if iteration_count % 100 == 0:
```

After running our codes, for the roundabout simulation, we received "**Total Iterations: 24**" printout. For the signalized intersection simulation, we received "**Total Iterations: 115**" printout. As seen from the last three comparisons, as the traffic light timing increases, the number of iterations for the last car to reach the point either $(-10, 0)$ or $(0, -10)$ increases by that much.

3.3. **Summary of Simulation Results.** Our simulations were accompanied by clear code visualizations and explanations to facilitate a comprehensive understanding of the results. These visual aids and explanations were essential for interpreting the impact of varying variables on the efficiency and speediness of roundabouts and signalized intersections.

In the following sections, we delve into a detailed analysis of the results, highlighting key findings and patterns that emerged from our simulations. We aim to provide a thorough evaluation of how changes in vehicle density and traffic light timings affect the performance of these traffic control systems.

4. Discussion

In this section, we analyze the outcomes of our simulations, considering the impact of varying vehicle density and traffic light timings on the efficiency and speediness of roundabouts and signalized intersections with traffic lights, as outlined in 1.3. We aim to provide a comprehensive understanding of the observed patterns, discuss the validity of our arguments, and communicate the reasoning behind our results.

4.1. **Patterns in Varying Vehicle Density.** The simulations we conducted in 3.1 focused on changing the number of cars while keeping other factors constant, particularly the traffic light timing which is set to 4. The results revealed these patterns:

4.1.1. *Stochastic Nature of Traffic Flow.* Traffic flow is stochastic and influenced by various unpredictable factors, including driver behavior, vehicle types, and unforeseen and disrupting events. While our simulations did not incorporate these factors, they still offered valuable insights into the consistency and variability of traffic patterns. Therefore, consequently, the simulations exhibited variations in performance metrics, leading to different outcomes under similar conditions.

4.1.2. *Variable Iteration Differences.* As we increased the number of cars, one notable observation we observed was the inconsistency in the iteration difference between roundabouts and signalized intersections. In some instances, this difference was as low as 1, while in others, it grew to 4. This phenomenon underscores the complexity of traffic interactions within simulations.

4.1.3. *Saturation Effect.* After reaching a certain vehicle density threshold (specifically, when we increased the number of cars to 11), the iteration difference between roundabouts and signalized intersections did not change. This observation demonstrates a saturation effect, indicating that the traffic systems might have reached a capacity limit beyond which additional vehicles do not significantly impact performance.

4.2. **Patterns in Varying Traffic Light Timings.** The simulations we conducted in 3.2 focused on exploring the influence of traffic light timings on traffic flow, with a constant number of cars set at 4. The results exhibited these patterns:

4.2.1. *Traffic Light Control.* Traffic light timings play a central role in governing the flow of vehicles at signalized intersections. Our simulations demonstrated that when we increased the timing to 10, the system reached a point of optimal synchronization, resulting in highly efficient traffic flow.

4.2.2. *Impact of Timing on Delay.* Lower traffic light timings (ranging from 1 to 5) led to increased delays and iterations due to insufficient green time for vehicles to clear the intersection. Beyond a threshold (in this case, 10), further increases in green time did not proportionally reduce delays, resulting in a consistent increase in iteration differences.

4.2.3. *Complex Interactions.* Our findings highlighted the interrelated and complex interactions between traffic light timings, vehicle densities, and their impact on traffic flow. Seemingly unexpected results, such as the pattern observed until a traffic light timing was set to 5, underscore the complexity of traffic simulations and the role of multiple variables.

4.3. **Relating Back to Research Objectives.** As stated in 1.3, our research objectives focused on assessing the efficiency and speediness of roundabouts and signalized intersections under varying conditions. While our simulations revealed unpredictable and interesting patterns, they also offered valuable insights into the nuanced dynamics of traffic control systems.

4.4. **Further Research.** The complex nature of traffic simulations provides opportunities for further investigation. Future studies could explore additional variables and factors that may influence traffic flow and shed more light on the observed patterns. Additionally, real-world data collection and validation of simulation results could provide a more comprehensive understanding of traffic control systems.

In summary, accompanied by clear code visualizations and explanations, our simulations have contributed to our understanding of the performance of roundabouts and signalized intersections. The variations observed underline the intricate nature of traffic flow, emphasizing the need for continued research and the importance of traffic engineering in optimizing transportation systems.

5. Limitations

While we conducted our simulations and drew inferences from them, it is still essential to acknowledge the boundaries of our approach and simulations. While our study provided valuable insights, it is important to recognize the limitations within which our findings can be applied. We grouped the following limitations into four categories:

5.1. **Simplifications in Simulation.**

5.1.1. *Homogeneous Vehicle Properties.* Our simulations assumed uniformity in vehicle driving behaviors, car properties, and traffic characteristics, which may not fully represent the real-world traffic diversity.

5.1.2. *Simplified Environment.* We conducted our simulations in a controlled and simplified environment, devoid of external factors such as weather conditions or road obstructions.

5.2. **Traffic Control System Assumptions.**

5.2.1. *Lack of Yellow Phase in Traffic Lights.* We did not consider the "yellow" phase in our signalized intersection simulation, which prevented our simulations from demonstrating realistic traffic light transition and affected intersection dynamics.

5.2.2. *Location-Specific Traffic Light Timings.* Fixed traffic light timings in our simulations did not account for location-specific adjustments based on different traffic regulations and conditions, time of day, or intersection characteristics.

5.3. **Vehicle Behavior and Realism.**

5.3.1. *Velocity and Acceleration Variability.* Variability in individual car velocities and accelerations, which can significantly influence traffic dynamics, was not considered in our simulations.

5.3.2. *Realistic Speed Changes Near Traffic Control Systems.* Speed adjustments that occur as vehicles approach traffic control systems were not modeled and considered, although they impact overall system efficiency and speediness.

5.4. **Scope and External Factors.**

5.4.1. *Roundabout Size and Rules.* Our study focused on a single standard roundabout size and a specific set of rules governing vehicle movements, which does not account for the diversity of real-world roundabouts.

5.4.2. *Scope of Simulation Variables.* While we examined vehicle density and traffic light timings, various other factors—such as road geometry, lane configurations, and driver demographics—were beyond our study's scope.

It is important to note that these limitations underscore the simplified nature of our simulations. While our simulations may not fully replicate real-world complexity of traffic dynamics, our study still provided valuable insights and laid the groundwork for future research in traffic engineering.

6. Conclusion

In the previous topics, we introduced and detailed our study by investigating the results we obtained and limitations we acknowledged. In this section, we talk about the key findings and implications of our study, while shedding light on the efficiency and speediness of roundabouts and signalized intersections under varying conditions. We also emphasize the significance of our work and its contribution to the field of traffic engineering.

6.1. **Key Findings.** Our simulations, while acknowledging their simplified nature, uncovered several noteworthy findings:

6.1.1. *Traffic Flow Complexity.* Traffic flow is inherently stochastic, influenced by numerous dynamic variables such as driver behavior, vehicle diversity, and external factors. Despite our simulations and models being simplified, our study revealed the complex nature of traffic dynamics, highlighting the challenges in replicating real-world conditions.

6.1.2. *Varying Vehicle Density.* The influence of vehicle density on the performance of roundabouts and signalized intersections showed unpredictable results. While an increase in vehicle density generally favored roundabouts, our results showed that the iteration differences varied, emphasizing the stochastic nature of traffic flow.

6.1.3. *Traffic Light Timing Optimization.* Our simulations underscored the essential role of traffic light timings in governing intersection efficiency. Notably, we found that increasing the timing to 10 led to optimal synchronization and highly efficient traffic flow, demonstrating the potential for optimization in signalized intersections with traffic lights.

6.2. **Implications and Future Directions.** These key findings hold significant implications for traffic engineering and transportation planning. As the number of studies conducted on this topic gradually increases, several opportunities for further research and practical application emerge:

6.2.1. *Real-World Validation.* Our study serves as a foundational exploration of traffic dynamics, albeit simplified. Therefore, future research can focus on validating our findings through real-world data collection and analysis, while providing a bridge between simulations and practical implementation.

6.2.2. *Advanced Simulation Models.* The complexity of traffic flow guarantees the development of more advanced simulation models that consider individual car behavior, diverse vehicle properties, and real-world traffic conditions. Such models can offer enhanced accuracy in predicting traffic dynamics.

6.2.3. *Location-Specific Traffic Control.* Adjusting traffic light timings to location-specific factors, such as traffic regulations and intersection characteristics, has the potential to optimize traffic control systems further. Research in this direction can contribute to more efficient urban planning.

6.3. **Closing Thoughts.** In conclusion, our research advances our understanding of traffic control systems' performance, even within the constraints of being simplified simulations. While we acknowledge the limitations of our approach, our study lays the groundwork for future investigations and underscores the intricate dynamics of different variables in traffic engineering.

Thus, we encourage researchers and practitioners interested in this dynamic field to delve deeper into it and explore innovative solutions to enhance the efficiency and speediness of current transportation systems. By continuing to bridge the gap between simulations and real-world applications, we can pave the way for more sustainable and streamlined traffic management.

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9. Appendix

In this section, we provide code samples that illustrate the implementation of the simulations discussed in this paper.

9.1. Roundabout Simulation Codes.

```
# Initializing car positions and states
x_cars = [8, 9, 10] # X Car 1 - X Car 2 - X Car 3
y_cars = [8, 9, 10] # Y Car 1 - Y Car 2 - Y Car 3

iteration_count = 0 # Variable to count the total number of iterations

```

```python
while True:
    for x in range(len(x_cars)):
        print("x", x, x_cars[x])
        if not (x_cars[x] - 1) in x_cars: # Making sure that there are no cars at the left of X cars
            if x_cars[x] == 1 and 0 in y_cars: # If the current X car is at 1 and Y cars are at 0, X cars will not move left by one unit
                continue
            x_cars[x] = x_cars[x] - 1 # The current X Car is moving left by one unit

    for y in range(len(y_cars)):
        print("y", y, y_cars[y])
        if not (y_cars[y] - 1) in y_cars: # Making sure that there are no cars at the down of Y cars
            if y_cars[y] == 1 and 0 in x_cars: # If the current Y car is at 1 and X cars are at 0, Y cars will not move down by one unit
                continue
            y_cars[y] = y_cars[y] - 1 # The current Y Car is moving down by one unit

    if max(x_cars) < -10 and max(y_cars) < -10: # If the biggest position of X cars and Y cars are smaller than -10, the code breaks
        break

    iteration_count += 1 # Increasing the iteration count by 1 in each loop

print("Total Iterations:", iteration_count) # Printing the total number of iterations
```

9.2. **Signalized Intersection Simulation Codes.**

```python
# Initializing car positions and states
x_cars = [8, 9, 10] # X Car 1 - X Car 2 - X Car 3
y_cars = [8, 9, 10] # Y Car 1 - Y Car 2 - Y Car 3

iteration_count = 0 # Variable to count the total number of iterations
traffic_light = 0 # 0 is Red in X direction and 1 is Red in Y direction

while True:
    for x in range(len(x_cars)):
        print("x", x, x_cars[x])
        if not (x_cars[x] - 1) in x_cars: # Making sure that there are no cars at the left of X cars
            if x_cars[x] == 1 and (0 in y_cars or traffic_light == 0): # If the current X car is at 1 and either Y cars are at 0 or the traffic light is Red in X direction, X cars will not move left by one unit
```

```
                continue
            x_cars[x] = x_cars[x] - 1 # The current X Car is moving left by one unit

    for y in range(len(y_cars)):
        print("y", y, y_cars[y])
        if not (y_cars[y] - 1) in y_cars: # Making sure that there are no cars at the down of Y cars
            if y_cars[y] == 1 and (0 in x_cars or traffic_light == 1): # If the current Y car is at 1 and either X cars are at 0 or the traffic light is Red in Y direction, Y cars will not move down by one unit
                continue
            y_cars[y] = y_cars[y] - 1 # The current Y Car is moving down by one unit

    if max(x_cars) < -10 and max(y_cars) < -10: # If the biggest position of X cars and Y cars are smaller than -10, the code breaks
        break

    if iteration_count % 10 == 0: # After each iteration, if the remainder is 0, the traffic light changes color
        print("Traffic Light is Changing", traffic_light)
        if traffic_light == 0:
            traffic_light = 1 # Changing the traffic light color
        else:
            traffic_light = 0

    iteration_count += 1 # Increasing the iteration count by 1 in each loop

print("Total Iterations:", iteration_count) # Printing the total number of iterations
```