Synchronizing Navigation Apps and Traffic Signals to Decrease System-Wide Travel Time

Grant Proposal

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Executive Summary

As the world population increases and more people are moving into urban areas, there has been an increase in traffic congestion around the globe, resulting in wasted time and an influx of carbon dioxide released into the atmosphere. Traffic signals and navigation apps are two systems independent from each other that have significant control over the flow of traffic. Fortunately, computational power has improved significantly and more people today are using navigation applications such as Google Maps. Therefore, it is plausible that traffic signals and navigation apps could be synchronized through a centralized computing system in order to improve the flow of traffic over an entire network. Creating a model for such a system is the goal of this project. This model will optimally and jointly assign routes for the vehicles in the network and set the traffic signals to minimize average travel time and fuel emissions. The model will build upon a previous study by adapting it to be suitable for a dynamic flow of traffic where vehicles can exit and enter the network. In addition, the model puts extra emphasis on fuel emissions due to the rising concern over greenhouse gasses. This model will be tested using NetLogo on a simple traffic network of four intersections in a two by two grid, and its performance will be compared to the current traffic systems. Its effectiveness will be measured by how much it reduces the average travel time and fuel emissions.

Keywords: traffic congestion, fuel emissions, route guidance, traffic signal optimization, dynamic traffic assignment

Synchronizing Navigation Apps and Traffic Signals to Decrease System-Wide Travel Time

Recently, traffic congestion has become a greater issue for drivers around the globe. With rapid population growth in cities around the world, the number of vehicles on the road has increased proportionally. Between 1980 and 2000, the US population grew by 24% while the total miles driven grew by 80% as a result of an increase in vehicle usage (Downs, 2004). Unfortunately, the current urban infrastructure does not accommodate for this increased demand in traffic. Consequently, roads from all around the country have faced an increase in traffic congestion. Not only does this increase the travel time for drivers, but it also is harmful to the environment due to greenhouse gas emissions. In 2004 alone, transportation was responsible for 33% of the CO_2 emissions in the US; of which 80% comes from vehicles on the roadway (Barth & Boriboonsomsin, 2008). Congestion also has a direct impact on human lives. Although vehicle speeds are slower during traffic congestion, research has shown that in general an increase in traffic congestion leads to an increase in traffic accidents as a result of more cars being on the road (Retallack & Ostendorf, 2019). Changing the current infrastructure would be impractical and expensive, so the best method for reducing traffic congestion would be to optimize existing traffic conditions by improving the control of traffic (Sanchez et al., 2010). Traffic signals and navigation apps are two systems that have an immense influence over the flow of traffic, so optimizing them would decrease traffic congestion and travel time.

Current Traffic Signal Models

Current models for traffic signals include fixed-time and actuated signals. Fixed-time signals follow predetermined rules, and provide the same amount of time to each traffic movement, whether traffic is present or not (Practical Engineering, 2019). Although these signals are acceptable during stable traffic conditions, events that disrupt the flow of traffic such as accidents or construction make them highly inefficient (Qadri et al., 2020). Therefore, most signals today are actuated, which use sensors to adapt to current road conditions (Practical Engineering, 2019). Actuated signals, ones that use sensors, are very flexible and can have adequate performance at a single intersection, but cannot effectively coordinate with other signals. Coordination is when adjacent traffic signals can communicate and influence each other in order for

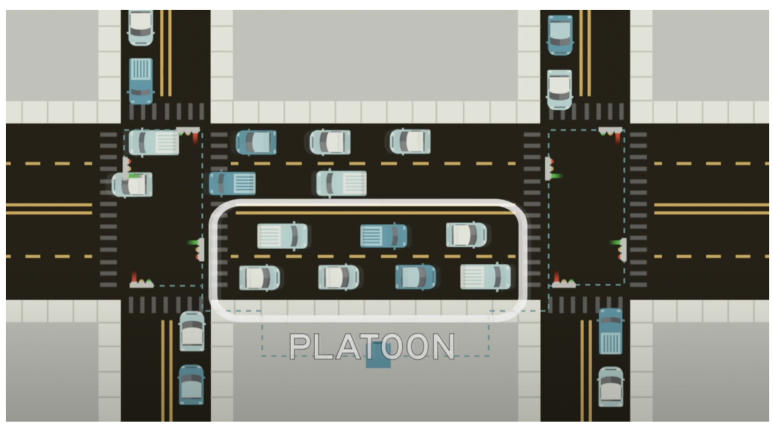

Figure 1. Two traffic signals synchronizing to let a platoon pass through (Practical Engineering, 2019)

vehicles to flow smoothly through both of them. One example of such synchronization is when they both turn green to let a platoon, a large group of cars, through. This phenomenon is illustrated in Figure 1. Although coordination between two traffic signals is not uncommon today, synchronizing over the whole network is the focus of new research into traffic signal optimization.

Previous Work In Traffic Signal Optimization

The problem of optimizing and often synchronizing traffic signals is called traffic signal optimization problem (TSO). A traffic signal phase is a group of traffic movements that do not conflict with each other. A normal two way intersection has four phases as shown in Figure 2, and the traffic signal will cycle through these four phases to clear out any cars waiting at the intersections. The TSO problem aims to find the optimal sequence and duration of each phase to minimize the average travel time in the network. Approaches to the traffic signal optimization problem can be classified into two categories: microsimulation-based approaches and computational intelligence-based approaches. Microsimulation-based approaches employ microsimulation techniques for the evaluation function during optimization (Qadri et al., 2020). Microsimulation in this context means running a simulation of the traffic network. Genetic algorithms, a type of machine learning, are commonly used in this field. One study used a genetic algorithm along with the use of cellular automata as their approach to TST (Sanchez et al., 2010). Cellular automata is a way to model a system using a grid of white and black squares. The use of cellular automata allowed them to model complex traffic situations such as overtaking and multiple-lane streets (Sanchez et al., 2010). The model was found to be highly effective for highly congested areas of traffic, but this was for optimizing fixed-time intersections (Sanchez et al., 2010). Computational intelligence based-approaches employ an estimation function to evaluate possible solutions in the search process (Qadri et al., 2020). One computational intelligence approach looking at an entire network in real-time used a metaheuristic along with the aid of the PARAMICS microsimulation software for a multi-objective performance model (Guo et al., 2019). It was found that there was a decrease in both total and average delay in the entire network (Guo et al., 2019).

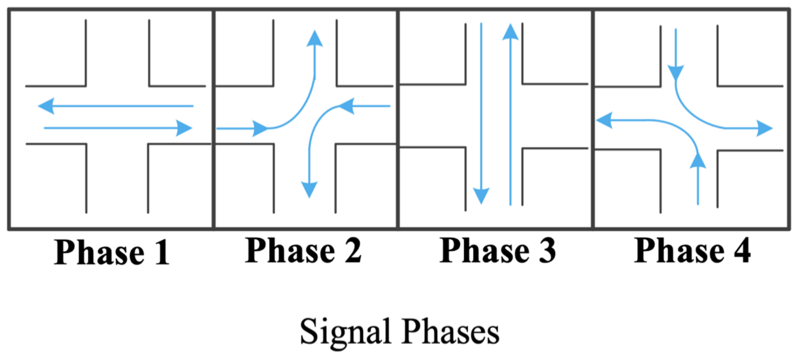

Figure 2. Four phases at an intersection (Li et al., 2015)

Navigation Applications And Traffic Equilibrium

Currently, when a traffic network gets congested, the network often goes into a state of user equilibrium. User equilibrium is where all paths taken by individual drivers are fastest for themselves only (Boyles et al., 2022). Unfortunately, user equilibrium is not optimal for the system as a whole, which leads to an increase in overall travel time (Boyles et al., 2022). Current navigation apps, such as Google Maps and Waze, allow users to input their desired destination, and output the fastest route to go there. This promotes user equilibrium as vehicles are following routes that are best for themselves but not for the system as a whole. User equilibrium is inferior to a system optimal state of equilibrium, where all paths taken by vehicles benefit the system (Boyles et al., 2022). User equilibrium has on average greater travel times and worse flow than system optimal equilibrium (Boyles et al., 2022). Therefore, there comes a need for navigation apps that benefit the system rather than focusing on the individual.

Previous Work In RGTSO

As discussed previously, the traffic signal optimization problem aims to optimize traffic signals to reduce network wide travel time. In addition, there is a need for navigation apps that can guide vehicles on routes which minimize travel times for the system rather than the individual. These two problems motivate research in the simultaneous route guidance and traffic signal timing problem, abbreviated as RGTSO, which is what my model aims to solve. The RGTSO problem is about creating a system where vehicles are guided upon paths by an external centralized system, and that system is also changing the timings of different traffic phases at signals in order for the network to have optimal flow. The problem was first formulated in 1994, where it was solved using an iterative approach after relaxing the problem constraints (Carey & Srinivasan, 1994). Constraints in this context means the different traffic rules, such as not overflowing the traffic capacity, having a valid path, and stopping at red lights. The constraints were relaxed using the method of Lagrangian relaxation, which is essentially removing conditions and adding them back onto the objective function. Another effective approach, which also used Lagrangian relaxation, was modeling the traffic network using a space-phase-time hypernetwork, and then use integer programming to optimize the routes given and the traffic signal timing (Li et al., 2015). The space-phase-time hypernetwork is the composition of a space-time network and phase-time network. A space-time network is a representation of the physical road network over time and can be used to show how the routes are chosen over the time period. A phase-time network shows how the different traffic phases of the signals at intersections are chosen over time. Integer programming is a general method of optimizing an integer function, and was an intuitive choice as Larangian relaxation is easily applicable for it. The hypernetwork was effective due to its flexibility and ability to represent complex traffic properties in understandable mathematics (Li et al., 2015). They tested the model on 960 and 480 vehicles in a network of 9 intersections in a three by three grid, and found that it was successful in reducing travel time (Li et al., 2015). However, this model does assume that the number of cars in the network remains constant with no new cars entering. This is not representative of realistic road conditions, as vehicles are always entering and leaving. In addition, it does not consider whether or not fuel emissions were reduced, specifically if the most optimal way to minimize travel time is the same as minimizing CO_2 emissions. These gaps will be taken into account in this study.

Section II: Specific Aims

This proposal's objective is to create a model for a centralized system that synchronizes navigation apps and traffic signals in order to decrease network wide travel time and fuel emissions. This system focuses on vehicles in a traffic network of intersections and roads. There are vehicles entering and exiting the system throughout. The assumption is made that all the cars in the network are using a navigation app to guide them. The system is connected to this navigation app along with traffic signals in the network. The users in the vehicles input their location and intended destination into the navigation app, and this information is then sent to the centralized system. The travel time is defined by how long it takes for vehicles to reach their destination. The system then uses this data to compute the most optimal routes for the current vehicles in the network to travel along and the optimal way to time the phases of the traffic lights. The system then sends the optimal path assignments back to every vehicle through the navigation app, and the traffic signals are given the best sequence of traffic phases.

Our long term goal is to apply such a system for a large network of intersections and roads in an urban environment. However, this is difficult computationally, so the model will be tested on a scaled down network.

Specific Aim 1: Create an algorithm that can simultaneously assign routes for vehicles and set traffic signals with given origins and destinations for all the vehicles to optimize system wide travel-time and fuel emissions.

Specific Aim 2: Test this algorithm on a network of four intersections on a two-by two grid with varying levels of congestion, comparing its performance to the status quo.

Specific Aim 3: Compare the solution that was found when optimizing travel time to the solution found when optimizing fuel emissions.

The expected outcome of this work would be a successful algorithm that can effectively minimize both travel time and fuel emissions over a network.

Section III: Project Goals and Methodology

Relevance/Significance

Traffic will only increase in the coming years, so the overall problem of congestion is relevant as the world population increases and more people move into urban areas. In addition, computing power is advancing and more people are using navigation systems such as Google Maps, which makes this model more plausible and effective as time goes on (Li et al., 2015). Finally, this system can be easily integrated into connected and autonomous vehicles, which will become more and more prevalent in the coming future.

Innovation

This model differs from the previous RGTSO models as it considers a network where the number of vehicles is dynamically changing. The aforementioned study using the space-phase-time hypernetwork solves this problem for a constant amount of vehicles (Li et al., 2015), but this is not an accurate representation of real-time road conditions. Instead, my model incorporates a constant flow of vehicles, which is based on real-life data. Testing with real-life data makes a traffic model more realistic as traffic dynamics are too complicated to be represented by made-up data (Qadri et al., 2020). In addition, with the growing world concerns over greenhouse gasses, this study puts emphasis on analyzing fuel emissions. The solution found to minimize travel time may not minimize fuel emissions, so this model will determine whether or not there is such a distinction, and will explore more relationships between the two variables. This has not been done with the previous RGTSO models.

Methodology

Specific Aim #1: Create an algorithm that can simultaneously assign routes for vehicles and set traffic signals, given origins and destinations of all the vehicles, in order to minimize system wide travel-time and fuel emissions.

Our approach to create this algorithm would be to adapt the previous RGTSO model to accommodate a dynamic flow of traffic with vehicles entering and leaving the system (Li et al., 2015). That is, rather than computing the optimal solution from scratch every time a new vehicle enters the system, the algorithm would look at the previous optima found and adjust it for the new vehicles. This method of optimization would save computational power that would be wasted if a new solution was found at every instant. The traffic network would be modeled using a space-phase-time hypernetwork, making expressing certain traffic properties easier mathematically. Specifically, it allows the objective function, the function that the algorithm optimizes, to be expressed as a relatively simple mathematical expression. Changing the objective function can change what parameters to minimize, so either travel time or fuel emissions can be optimized by altering this function. When optimizing fuel emissions, the fuel efficiency of each car will be accounted for which is a constraint that was not considered in the previous model.

Justification and Feasibility.

This model is building off of a previous successful RGTSO model that was able to reduce average travel time by assigning routes and setting traffic signals (Li et al., 2015). Therefore, since this model is adapting a working model to be dynamic, it should be able to minimize travel time if adapted correctly. The space-phase-time hypernetwork is flexible to changes so such an adaptation is feasible. Although the previous model focused on minimizing travel time, it does state that other optimization criteria could be considered so minimizing fuel emissions is feasible (Li et al., 2015).

Expected Outcomes.

The overall outcome of this aim is an algorithm that can compute the routes and traffic signal timings that optimizes travel time or fuel emissions. This will serve as the foundation of the model, and will be used for testing in a simulated traffic network.

Potential Pitfalls and Alternative Strategies.

A possible pitfall is that adjusting the previous model to be dynamic may not be computationally reasonable. If such a problem occurs, the algorithm could be specifically coded for the two by two grid of intersections that is tested instead of a general network. This would decrease computation time, but would also decrease the scope of inference.

Specific Aim #2: Test this algorithm on a network of four intersections on a two-by two grid with varying levels of congestion, comparing its performance to the status quo.

Our approach would be to test the algorithm using the NetLogo agent-based-modeling software. Agent-based modeling is a way of simulating interactions between autonomous objects known as “agents”. Here, the agents will be the vehicles in the system. In NetLogo, a network is represented by a grid of small squares, also known as cellular automata. The two by two grid of intersections and the lanes connecting them will be composed of cellular automata and made in NetLogo. From here, the algorithm for minimizing travel time will be tested on traffic scenarios of varying levels of congestion. After the algorithm computes the optimal signal timing and routes, the simulation will be run and the average travel time can be computed. In addition, the status-quo model will also be tested. This current-day model will be represented by fixed-time signals and vehicles traveling along paths that Google Maps tells them. This model will be tested on the same traffic scenarios and the average travel time will be computed. Afterwards, the same testing process will be done for when the algorithm is minimizing fuel emissions, with average fuel emissions being calculated instead.

Justification and Feasibility.

NetLogo was chosen as the testing software due to its simplicity and capability of modeling traffic dynamics. The algorithm can be implemented as simulations in NetLogo can be programmable. The size of the network, a two by two grid of intersections with four total, was chosen as it is complex enough to demonstrate route assignment, but simple enough to be feasibly tested with appropriate computational power. When testing the current-day model, the Google Maps API can be used to determine how Google Maps would have assigned the vehicles. This testing process is feasible, as the previous RGTSO model was tested on a three by three grid of intersections with 960 vehicles, and only took 90 seconds to find the optima. This means that the computation time required is at an appropriate order of magnitude.

Expected Outcomes.

The expected outcome of the testing is that our model was able to significantly reduce average travel and fuel emissions when compared to the current traffic systems. This would show that our system was indeed effective in improving traffic flow and decreasing greenhouse gasses.

Potential Pitfalls and Alternative Strategies.

Although the Google Maps API is easy to obtain, it may prove to be difficult to use when testing due to a delay in requests (Wang & Xu, 2011). If this pitfall makes the computation time of testing the status-quo model unreasonable then the API will not be used. Instead, the routes of the vehicles in the status-quo model would be randomly assigned a shortest physical path. In the two by two grid of intersections, there are at most two equally short paths to get from an origin to a destination, so random assignment could replace Google Maps.

Specific Aim #3: Compare the solution that was found when optimizing travel time to the solution found when optimizing fuel emissions.

Our approach for this aim is to keep track of the solution found by the algorithm during testing when optimizing travel time and the solution found for minimizing fuel emissions. These solutions consist of all the path assignments of the vehicles and the timings of the signals. From there, comparing individual routes of vehicles and the phase sequences of the traffic signals from the two solutions, a measure of similarity can be calculated by counting how many correspond.

Justification and Feasibility.

This approach is feasible because if the algorithm is successful, then it should be able to compute the solutions for both minimizing travel time and signal timing. Once the solutions are found, analyzing their similarity can be as simple as using a for loop, so this is feasible.

Expected Outcomes.

The expected outcome would be a confirmation for whether or not the solution for minimizing travel time is the same as for minimizing fuel emissions. This knowledge would provide insight for whether or not there is a need for traffic models to take fuel consumption in consideration. If no difference was found in solutions, then traffic models could only focus on optimizing travel time as that would also optimize fuel emissions. However, if there was a difference then that would suggest that travel models should take fuel consumption into account in order to be ecologically respectful .

Potential Pitfalls and Alternative Strategies.

If there are indeed differences, then a simple algorithm for counting how many routes correspond does not indicate how much they correspond, but rather if they match exactly or not. This could be a pitfall if there is a need to measure similarity more precisely. An alternative strategy of computing similarity would be to calculate both fuel emissions and travel time during all test cases. If the average travel time for minimizing fuel emissions is similar to the travel time found when minimizing travel time, then that could indicate that the solutions are similar.

Section III: Resources/Equipment

This study will use the NetLogo software for testing, which requires only a home computer to run. NetLogo is a free software.

Section IV: Ethical Considerations

There are no known ethical concerns or risks in this study.

Section VI: Timeline

This project was started on September 1st, 2022, and must be completed by March 15th, 2023. The Gantt chart shown below is a visual timeline, and will be updated regularly.

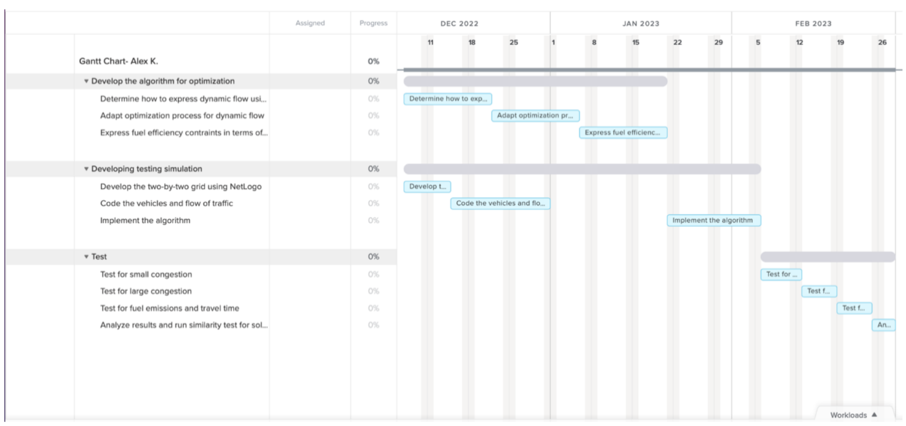

Figure 3. Gantt Chart showing timeline of project (Kaneko, 2022)

Section VII: Appendix

Section VIII: References

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