Project 2.2: Research of Architecturally Efficient Interchanges in Automobile Transportation Networks

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1 Abstract

The goal of this project is to evaluate different automobile transportation network intersections, comparing the flow, average travel time and average traffic speeds therein. The simulation environment used a Poisson arrival process to simulate real-life behavior of the cars. It was concluded that changes to the infrastructure dramatically improve the traffic flow and traveling speed compared to intersections with traffic control lights.

2 Introduction

As the world's population grows, the growth of urban centers far outpaces the growth of rural communities, leading to areas of high density facing crippling traffic congestion in automobile transportation networks [5]. As these communities grow, advanced traffic control strategies will need to grow and adapt to keep pace with population growth. Research into this field is prolific, and significant investment has been made in minimizing automobile traffic delays utilizing traffic control schemes. However, developing countries as well as countries with significant geographical space such as China and the United States have the distinct advantage of being able to plan new networks from scratch, compared to already existing networks in historically significant regions such as central Europe.

Due to an already high population density, countries such as the Netherlands face the challenge of updating and building new networks without relocating or demolishing existing buildings, which often have high historical or cultural significance. This naturally leads to an emphasis on the optimization of traffic control strategies on already existing networks, compared to building newer, more architecturally efficient networks. However, as the amount of vehicles on the road continues to increase, the question arises if optimization of current networks has an upper bound.

This paper examines the potential benefits and drawbacks of architectural design of new, more efficient forms of intersections that may allow for a higher throughput of vehicles without the need for traffic control lights, positing the research question *"What is the potential benefit of an architectural change in intersection design when compared to a traditional intersection governed by a static control scheme?"*.

A number of existing types of intersections and interchanges are implemented, some with traffic lights and others without, and multiple observations are made for statistical comparison. Metrics such as the total amount of vehicles capable of navigating the intersection in a given time frame, the average time taken to traverse the intersection, and the average speed while traversing the intersection are compared.

The choice of intersection types used is based on a study of literature of popular intersection and interchange types used commonly throughout the world [7]. Traffic light control schemes are based on various static intervals.

2.1 Problem Statement

Given a selection of intersection types, one of which contains traffic control lights and others using non-planar structures, the challenge is to develop a simulation environment that can realistically simulate traffic flow through these intersections.

In order to maintain symmetry and therefore a statistical standard, the intersections all must contain the same default settings, such as the number of lanes and speed limit when approaching the intersection, in order to preserve the integrity of the statistical inferences made based on the throughput and efficiency of each intersection.

The goal of this project is to minimize the average travel time for all vehicles to reach their destination from start to finish, and to evaluate which interchange is most robust against heavy and noisy traffic and which is the most efficient in terms of collision and throughput.

3 Modern Traffic Modeling Software

Traffic simulation for optimization purposes is far from a modern phenomenon, and there exist many types of traffic simulation software to achieve this purpose. One of the most popular software environments used in the modeling of European road networks is SUMO (Simulation of Urban Mobility). SUMO is a continuous, microscopic and multi-modal traffic simulation [4] [1]. The SUMO software has multiple similarities with the simulation built in this research, such as collision free vehicle movement and the simulation of real-world networks via input from XML files. The software is also capable of handling different vehicle types and multi-lane streets with lane changing, which is not included in this project at this phase. A weakness of the SUMO simulation is the traffic light strategy, as only simple implementation of traffic light interval timing is integrated. Besides the normal validating procedure, the SUMO software could be used to validate the simulation for simple traffic light strategy.

4 Modeling Realistic Road Networks

NetEdit, a proprietary software package contained within SUMO, allows for the import and modification of real-life road networks via the OpenStreetMaps.org website [6]. With NetEdit it is possible to import real-life networks as a .net file (a proprietary file type) and then convert the information contained in the .net file into a list of nodes and edges, each of which contain real-life information regarding their location in 2-dimensional space relative to one another, which roads are connected, the speed limit of each road, and the number of lanes for each road.

For this project, a number of intersections were found on the OpenStreetMaps.org website and exported to NetEdit, where they were isolated and altered to be of the same size, contain the exact same number of lanes, and respec the same speed limit, in order to create a standard basis upon which to conduct experiments.

4.1 Simulating Realistic Traffic Patterns

To properly model realistic traffic patterns, vehicles are given a starting and ending location at the entrances and exits of the intersection (such that no vehicle spawns "inside" the intersection) and are chosen based on a uniform random distribution. Vehicles observe the laws of the road according to the Intelligent Driver Model, and follow the shortest path to their goal [8].

Furthermore, in order to introduce noise into the model, the factor by which vehicles adhere to the speed limit is determined by a Gaussian distribution with a mean of 1.0. Additionally, multiple iterations of experiments are performed with differing standard deviations in the distribution, introducing an exponentially increasing variance in randomness of driver behavior[9]. The incremental increase in standard deviation was introduced as a means to determine how robust each intersection is to changes in individual driver's behavior, as compared to a constant uniform "stream" of traffic all adhering to the speed limit exactly.

The arrival times of vehicles during the simulation is determined via a Poisson arrival process, allowing for a varying rate of arrivals throughout the simulation and allowing for the simulation of both low and high arrival rates to further test each intersections capability of handling abrupt changes in traffic conditions.

5 Traffic Flow Optimization Strategies

In this project, the only intersection type containing a traffic light control scheme is a standard 4-way intersection known as the 4-way at-grade junction, where a typical lighting scheme of green and red lights controls whether a lane is allowed to progress forward, turn left/right, or stop.

The remaining intersection types do not have any form of traffic lights and rely entirely on their structure to direct the flow of traffic, which are described in section 6. Furthermore, these intersections are "non-planar" such that when two individual roads meet (each with opposing lanes of flow), one road passes over the other such that these two roads never meet. This can be described as a non-planar graph such that the intersection of two edges does not contain a node between these edges. An example of a non-planar intersection can be found in figure 4.

5.1 4-Way At-Grade Junction

The traditional 4-way intersection 1, the 4-way at-grade junction is an (often perpendicular) intersection of 2 roads, each with 2 opposing lanes of traffic. At this intersection, the traffic control lights on opposite sides of the intersection enumerate between two states - red and green. While two opposing directions of flow are in one state, the other two directions of flow are in the other, i.e. while north/south is green, east/west is red. In certain circumstances, certain lanes of the north/south road may be green while other lanes in the east/west road may also be green, i.e. the right turn lane for north/south being green while the left turn lane for east/west is also green.

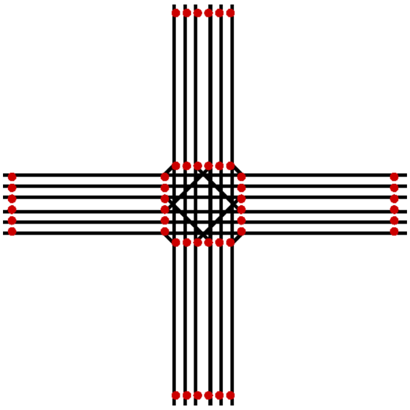

Figure 1: Regular Interchange with stoplights

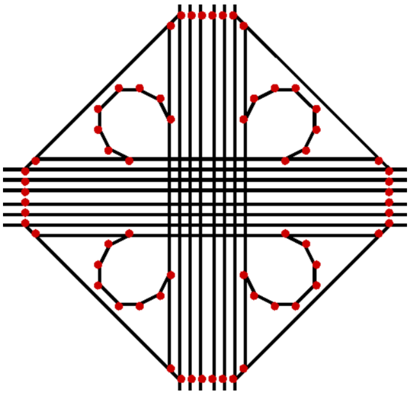

Figure 2: Cloverleaf interchange

5.2 Traffic Light Control

A traffic control timing scheme on a static interval is implemented such that the lights cycle between red and green for the duration of the interval. In this model, the static interval of 100 seconds is used. This interval does not change throughout the simulation, and is used as a baseline with which all other strategies will be tested and compared against.

6 Architectural Network Optimization

Architectural modification of existing road networks is costly in time, resources, and space. Furthermore, the type of changes depends heavily on the current volume of the existent (sub)network, and there are multiple alternatives to traditional 4-way stoplight intersections. In this project several types of non-planar interchange structures are compared to these traditional intersections, which are detailed in the following section.

6.1 Non-planar Interchange Structures

The purpose of a non-planar interchange is to eliminate the need for traffic control lights, which additionally eliminates the need for vehicles to stop and wait for others to pass, with the goal of maintaining a constant throughput in all directions and reducing traffic buildup.

Cloverleaf Interchange

The cloverleaf interchange is a junction of two highways, one crossing over the other, with multiple exit and entrance ramps. The ramps are in the middle shaped like a four-leaf clover, so the traffic from can proceed to every direction without the need for stopping and drastic speed reduction .

Single Point Interchange

The single-point interchange, also called single-point diamond interchange, has the advantage that it increases safety as well as reduced right-of-way requirements compared to other interchanges. Because the traffic can be controlled with one single signal, or with planar design even without one, vehicles can clear the intersection much more quickly than in a normal diamond interchange. The major disadvantage of a single-point interchange over other types of road junctions is the increased cost due to the wider bridge that is needed over the crossing highway.

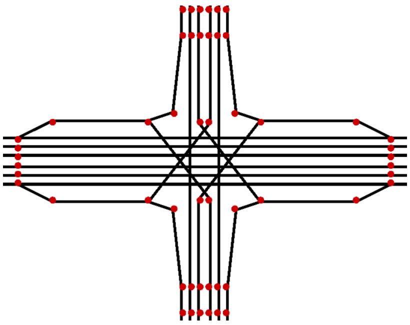

Figure 3: Single Point interchange

Turbine Interchange

The turbine interchange is a four-level stack interchange. The exiting and entering ramps sweep around the center of the interchange in a spiral pattern, as can be seen in figure 5. Therefor the vehicles speed can retained a speed through the intersection that does not deviate drastically from the approaching speed.

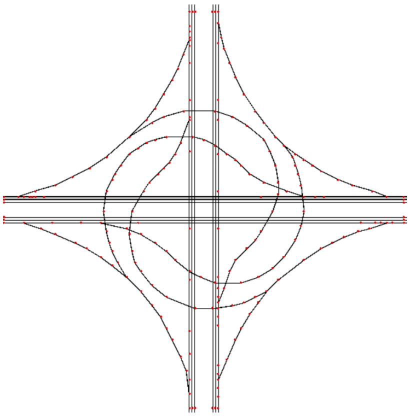

Figure 4: Turbine interchange

Pinavia

The Pinavia is a unique 2-level road junction that aims to maximize capacity and safety, while allowing for the utility the "free space" in its center [2]. The Pinavia, designed by Stanislovas Buteliauskas in 2004, has advantages such as its high multi-directional capacity, safety, and allowance of innovative transportation and urban management strategies with the use of the area within the center of the junction itself. It also is capable of maintaining constant speed and can be applied universally, in the way it is applicable to intersections with three, four, and even five roads and can even intersect roads which differ. The biggest advantages are the safety and the efficiency of the junction, as there are no conflicts anywhere in the intersection meaning in optimal conditions there is no need to merge or slow down.

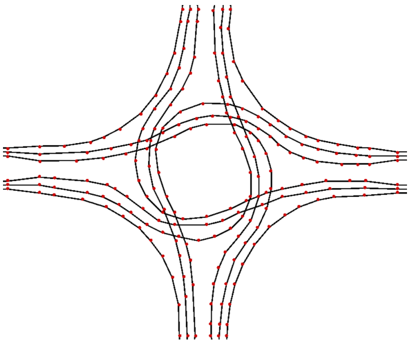

Figure 5: Pinavia interchange

7 Experiments

In this project, a series of simulations are computed for each intersection type. Various metrics are measured, and the results of each intersection's performance is statistically analyzed and compared to other intersection types. The experiment takes six different metrics into account in order to determine how effective each intersection/interchange design is able to handle varying volumes of traffic, determined by the random vehicle arrival rates described earlier. These six metrics are:
[3]

1. **Traffic Flow**
   The number of vehicles that pass a certain point in a certain period of time, calculated for one direction of traffic.
2. **Realised Travel Time (RT Time)**
   The arithmetical average of the time taken for all vehicles arriving at the end point of a travel time section during one minute to have traveled from the start point to the end point of that travel time section, calculated for one direction of traffic.
3. **Estimated Travel Time (ET Time)**
   The approximate time taken for all vehicles arriving at the start point of a travel time section during one minute to travel to the end point of that travel time section, calculated for one direction of traffic. An estimation method is used to calculate this.
4. **Traffic speed**
   The average speed of vehicles that pass a point in a unit time, calculated for one direction of traffic.
5. **Total number of cars that reach their goal**
   As the standard duration of the simulation is one hour or 3600 ticks and cars are spawned throughout time, many cars will not have the time to reach their goal because they spawn too late. This is why it is needed to measure how many cars actually reach their goal in order to give other statistics.

Generating these metrics gives the ability to compare the intersections by their mean results (experiments: 1, 2, 4, 5, and 6). By generating 95% confidence intervals of the observed data, the range of possible true values of the unknown mean value can be computed.

$$\bar{X}(n) \pm t_{n-1,1-\frac{\alpha}{2}}\sqrt{\frac{S^2(n)}{n}}$$

where $t_{n-1,1-\frac{\alpha}{2}}$ is the critical value for significance level α and $n-1$ degrees of freedom.

The Dudewicz and Dalal procedure can be used to determine the number of simulations needed to reach the desired confidence interval. The total sample size is given by following function

$$N_i = \max(n_0 + 1, \frac{h_1^2 S_i^2(n_0)}{(d^*)^2})$$

where h_1 is depends on P, level of certainty, k, the amount of systems compared and n_0, amount of runs.

8 Results

The results are gathered from running 10 simulation on each intersection. The tables in appendix 1 hold the metric values of experiments 1 through 6. The tables shown in appendix 2-4 hold the other statistical results of each experiment.

9 Discussion

Intersection Efficiency

The 4-way Intersection was clearly the slowest intersection to traverse, as the average traffic speed over the course of an hour was more than 20cm/second slower than even the second slowest interchange type. The standard deviation of the average speed of each vehicle was also significantly higher by a factor of almost 30.

This leads to the observation that requiring vehicles to stop while waiting for others is less efficient than interchange structures that do not have any form of traffic control lights.

Traffic Flow

An anomalous result was observed in the simulation of the turbine interchange, as the traffic flow was significantly lower than other interchanges, including the 4-way intersection. During simulation it was realized by the researchers that the gross size of the Turbine and Pinavia interchanges were significantly larger than their counterparts, leading to a lower number of vehicles that were able to reach their goal in the allotted simulation time. This anomaly could not be accurately accounted for in the time allotted, hence the wide discrepancy.

However, observation of the standard deviation of the average speed of each vehicle in these interchanges demonstrate that the turbine and Pinavia interchanges have the lowest discrepancy in speed across all vehicles traversing the interchange. This leads to the conclusion that regardless of the size of the interchange, vehicle throughput on the turbine interchange is indeed the most efficient of the interchanges researched in this project.

In close second and third place are the single point and Pinavia interchanges in terms of average vehicle speed deviation. The single point intersection reduces the number of individual lanes intersecting, thereby reducing the potential for bottlenecks. The Pinavia interchange has no intersecting lanes whatsoever, leading to a higher level of traffic flow.

10 Conclusions

This project focused on the architectural structure of interchanges and their efficiency, in further research other traffic control components can be researched such as a global network communicating with each vehicle to prevent congestions, or improved controls such as smart dynamic traffic lights.

When taking into consideration various metrics such as the standard deviation of average vehicle speeds, the average traffic speed, and the tightness of the confidence interval, it is clear that the 4-way junction is the least efficient intersection type. However, it is not possible to definitively state based on this project's results that there is a single interchange type whose efficiency far exceeds one another, except the 4-way junction.

It is therefore the conclusion of this project's researchers that any form of interchange that does not require any form of stoplight control mechanism is more efficient than one that does, given no restrictions on space. Future research could be conducted in comparing various dynamic traffic light control schemes with architectural improvements to better determine the true efficiency of architectural changes versus optimized light control schemes.

11 Appendices

Table 1: Simulation results

Intersections	**Metrics**				
	Traffic Flow [a]	**RT Time[b]**	**ET Time [c]**	**Traffic Speed [d]**	**ST Dev[e]**
4 Way Intersection	645	1311	1279.32	12.72	1.1097
Turbine Interchange	206	1705	1706.37	12.94	0.0311
Cloverleaf Interchange	628	1332	1333.18	12.96	0.0565
Single Point Interchange	656	1208	1208.66	12.96	0.0312
Pinavia Interchange	345	2296	2297.40	12.95	0.0313

Table 2: Confidence interval for traffic speed

Intersections	**95% Confidence Interval**
	Traffic Speed
4 Way Intersection	$[12.72 \pm 0.688]$
Turbine Interchange	$[12.94 \pm 0.0193]$
Cloverleaf Interchange	$[12.96 \pm 0.0209]$
Single Point Interchange	$[12.96 \pm 0.0194]$
Pinavia Interchange	$[12.95 \pm 0.0225]$

[a] Traffic Flow (cars/ hour), [b] Realised Travel Time (seconds), [c] Estimated Travel Time (seconds), [d] Traffic Speed (meter / seconds) , [e] Standard Deviation

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