# The Effectiveness of Autonomous Intersections in a City

**Eliáš Cizl**
Charles University
Prague, Czech Republic

**Jiří Švancara**
Charles University
Prague, Czech Republic

**Roman Barták**
Charles University
Prague, Czech Republic

## Abstract

Vehicle navigation on roads is a complex problem that will probably be solved by using artificial intelligence in key roles. Today, there are cars capable of autonomous driving, but they are dependent on an old infrastructure that primarily includes intersections designed for human drivers. This paper opens a new chapter in the area of autonomous intersection management. Most research to date has looked at implementing a solution for a single intersection. We have created a simulation that runs in real-time, where up to several dozen intersections appear side by side. In this work, we conduct experiments to test the deployment of the autonomous algorithm in a city along with traffic lights. Autonomous intersections win with their efficiency, and in case of a limited budget, it's most advantageous to deploy them at the busiest intersections.

## Introduction

Personal (and other) transportation is one of the key aspects of our daily reality. While cars don't provide the safest (Liu and Moini 2015) nor the fastest means of travel (not to mention the ecological sustainability), they are still being used in big quantities and it makes sense to try to optimize various parts of this area using artificial intelligence. The main view is currently focused on single vehicles by improving sensors and navigation capabilities (Badue et al. 2021). However, it is also logical to look at the cooperation of multiple agents and multiple intersections (Goldstein and Smith 2018). In this work, we explore the topic of *autonomous intersection management* (Dresner and Stone 2008).

Intersections are a "hot place" where many traffic lanes cross, merge, and divide. It's rational to concentrate on improving this part of the system. With vehicles capable of wireless communication with each other (or some other elements of the network) within milliseconds, the idea of replacing standard mechanisms like traffic lights becomes very realistic.

The contribution of this paper is exploring the interaction of multiple connected intersections. To this extent, we create a simulation framework and perform experiments. We try to answer the following questions. What if we started replacing some traffic lights with autonomous systems? Where does it make the most sense to put these smart control mechanisms?

## Simulation

To answer the proposed questions, we developed a simulation capable of running hundreds of cars at the same time.

**Vehicle Representation.** The simulated vehicles are fully autonomous and able to communicate with each other and other parts of the simulation. They are represented by boxes. The vehicles accelerate and decelerate linearly. Acceleration changes constantly. Vehicle navigation (maintaining distance, changing lanes, following trajectories, etc.) is done entirely in code and is assumed to be perfectly executed.

**City Generation.** Many options to artificially generate roads that resemble real scenarios exist (Shi, Shen, and Liu 2009). We decided to implement a very basic, though common, model which is a square grid with four-legged intersections. Not all directions need to be present which allows many possible configurations. The concept of *main* and *side* streets (or roads) is present. First, the main roads are generated regularly separated, or randomly placed. Then, the side roads are generated to fill the gaps, or placed randomly. The number of lanes for each type of street can be set. Intersections are generated at the crossing points of the roads on the grid. All incoming and outgoing directions that can be connected are connected. Based on these connections, trajectories are generated to be used by the traversing vehicles. See Figure 1 for an example of a generated city.

Vehicles spawn at the edges of the city (ends of the grid roads), from where they travel to another random exit (the probability distribution is based on selected settings). The path between the two points is calculated using a simple A* algorithm (Hart, Nilsson, and Raphael 1968) that takes into account only the distance and not the current traffic.

**Intersection Algorithms.** Three different intersection management algorithms were implemented.

*Stop signs*. Only one vehicle may be present in the intersection at a time. The order is given by the time of arrival at the intersection.

*Traffic lights*. One incoming direction (all lanes from that direction) goes at a time. After a set period, the active direction changes to a different one. This is further improved by allowing lanes that are guaranteed to not have a collision with any of the active directions to move.

---

| Configuration | | Total distance traveled (m) | Distance improvement per intersection (m) | Average delay (s) | Delay improvement per intersection (s) |
|---|---|---|---|---|---|
| Traffic lights only | 0 | 11384240 | — | 96.98 | — |
| Main junctions only | 4 | 12264680 | 220110 | 85.26 | 2.930 |
| Random selection | 8 | 12159260 | 96878 | 86.26 | 1.339 |
| The busiest | 10 | 13562790 | 217855 | 70.31 | 2.666 |
| The busiest | 20 | 15817050 | 221640 | 50.11 | 2.343 |
| Main roads | 24 | 16831910 | 226986 | 42.66 | 2.263 |
| Side roads | 25 | 14877830 | 139744 | 57.72 | 1.570 |
| Random selection | 38 | 19645250 | 217395 | 26.27 | 1.861 |
| AIM only | 49 | 25538420 | 288861 | 3.31 | 1.912 |

Table 1: Measured results for 500 vehicles with various placements of AIMs. The *Configuration* represents the placement strategy with the number of placed AIMs. The improvement per intersection is measured as the difference between *Traffic lights only* and the given strategy divided by the number of used AIMs.

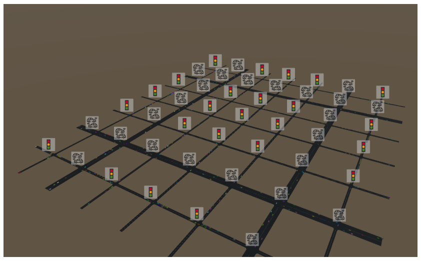

Figure 1: Generated city with highlighted algorithms used at each intersection.

*Autonomous intersection management (AIM).* The general scheduling policy is *first come, first served* in a centralized manner (Khayatian et al. 2019). The vehicles follow a predefined trajectory and create a blocking time window on each point that crosses any other trajectory. The following vehicle is scheduled to traverse its trajectory as fast as possible avoiding the blocked windows. While simple in principle, many issues had to be solved to avoid collisions. As the vehicles have non-instant acceleration, buffer zones had to be added in front of the intersection to take over the vehicles and slow them down if necessary. Similarly, as intersections influence each other, buffer zones behind the intersection had to be added to detect if there is a congestion. A new car is allowed to traverse the intersection only if there is enough space for it to leave the intersection safely.

## Experiments

To test the performance of different algorithms, we conclude experiments in a city-like setting. The generated city is made of 7x7 intersections with 4 regularly placed bidirectional 3-lane main roads and the rest is filled with bidirectional 1-lane side roads. The city can be seen in Figure 1. The spawning distribution was set so that half the vehicles appear at main entrances – 80 % of them also going to main exits. Out of the other half, 60 % were designed to travel to a main road exit. This way we ensure that the main streets are used for the majority of traffic.

Table 1 shows the measured results. The configuration describes locations where the AIMs replaced traffic lights. The number next to the configuration name shows the total number of AIMs in the system. The total distance traveled corresponds to throughput. Recall that the cars choose their path independent of traffic, so for a single vehicle, the distance is always the same regardless of the intersection algorithm. However, the more vehicles pass through the system, the larger total distance traveled is accumulated. We provide this metric instead of the number of vehicles to take into account the length of the paths and thus the number of intersections on the traversed path. Average delay measures the delay compared to traveling in a system with no other vehicles. The improvement per intersection is an improvement over *Traffic lights only* divided by the number of AIMs in the system.

The most naive approach is to choose the locations randomly. This option performed rather poorly even compared to setups with fewer AIMs in total. A sensible way of choosing is by city design. There are three types of junctions: main road only, main and side roads, and side roads only. In the table, *main junctions only*, *main roads*, and *side roads*, respectively. Alternatively, AIMs can be placed by the busyness of a particular intersection. The busyness of one intersection is calculated beforehand based on the grid topology and spawn distributions. All options were tried – using AIM at the busiest, at the least busy, and at the "middle" ones. Only the option of choosing the busiest was performing well, hence the others are omitted from the table. Placing AIMs by the busyness of an intersection performs similarly to placing them by design – the main junctions get the most traffic. However, here we can finetune the exact number of intersections to be coordinated by AIMs.

In summary, the best performance is achieved by replacing all traffic lights with AIMs. However, in case of a limited budget, it is sensible to deploy AIM at intersections that may be expected to experience the heaviest traffic.

## Acknowledgments

This work was funded by project 23-05104S of the Czech Science Foundation, and by CUNI project UNCE 24/SCI/008.

# References

Badue, C.; Guidolini, R.; Carneiro, R. V.; Azevedo, P.; Cardoso, V. B.; Forechi, A.; Jesus, L. F. R.; Berriel, R. F.; Paixão, T. M.; Mutz, F. W.; de Paula Veronese, L.; Oliveira-Santos, T.; and Souza, A. F. D. 2021. Self-driving cars: A survey. *Expert Syst. Appl.* 165:113816.

Dresner, K., and Stone, P. 2008. A multiagent approach to autonomous intersection management. *Journal of artificial intelligence research* 31:591–656.

Goldstein, R., and Smith, S. F. 2018. Expressive real-time intersection scheduling. In *Proceedings of the Thirty-Second AAAI Conference on Artificial Intelligence*, 6177–6185. AAAI Press.

Hart, P. E.; Nilsson, N. J.; and Raphael, B. 1968. A formal basis for the heuristic determination of minimum cost paths. *IEEE transactions on Systems Science and Cybernetics* 4(2):100–107.

Khayatian, M.; Lou, Y.; Mehrabian, M.; and Shirvastava, A. 2019. Crossroads+: A time-aware approach for intersection management of connected autonomous vehicles. *ACM Trans. Cyber-Phys. Syst.* 4(2).

Liu, R., and Moini, N. 2015. Benchmarking transportation safety performance via shift-share approaches. *Journal of Transportation Safety & Security* 7(2):124–137.

Shi, W.; Shen, S.; and Liu, Y. 2009. Automatic generation of road network map from massive gps, vehicle trajectories. In *2009 12th international IEEE conference on intelligent transportation systems*, 1–6. IEEE.