FPolyOS: A Simulation Platform to Explore Breakthrough Concepts in Intelligent Transportation

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Abstract—Today, transportation planners are asked to optimize the transportation system such that every participant has minimal latency while the costs of the overall infrastructure are minimized. The tools at hand focus on road design, signage, and traffic light management. These tools are coarse-grained and must manage a variable degree of compliance from human drivers. Overall, this is a very difficult task. Perhaps the biggest opportunity for the transportation system is the electronics technology revolution, which makes many powerful tools available. These include the availability of customer point-to-point information (cellphone applications), dynamic traffic management (smart lights), and directive agents (Autonomous Vehicles or Commercial Fleets). Further, with the availability of these tools, fundamentally new customer engagement models can be enabled to optimize the transportation system. In this paper we present FPolyOS, a next generation simulation environment, which is built to explore break-out models enabled by bottom-up electronics infrastructure. FPolyOS is differentiated by exploring concepts such as micro-tolling and dynamic traffic management combined with a top-down market based optimization paradigm.

Index Terms—Autonomous Vehicles, Connected Vehicles, Simulation, MATSim

I. INTRODUCTION

In today’s transportation system, transportation engineers try to optimize the system such that every participant has minimal latency while the costs of the overall infrastructure are minimized. The tools of the trade include road design, signage, and traffic light management. Because of the variable compliance by all human drivers, the level of control is coarse in this scheme. In network engineering terms, the level of error and variability can be very high which leads to a level of optimization which is limited.

With the advent of the electronic technology revolution, many powerful tools have become available to the transportation ecosystem. The key technologies which are coming online include:

- Point-to-Point Trip Information: Mapping applications such as Waze, Apple Maps, or Google Maps contain a rich level of information of the overall intended trip for the customer.
- Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication: V2V and V2I communication has been traditionally conceived with a focus on safety [1]. However, another, perhaps more interesting, application is communication for the purposes of traffic management with concepts such as micro-tolling.
- Smart Infrastructure: Traffic systems which are cloud connected can enable controls which can further optimize traffic flow dynamically [2].
- Fleet Creation: With the advent of cellular and ad hoc connectivity, individual drivers are becoming parts of fleets. Fleets include trucking companies, shared mobility companies (Uber), and public services (police, fire department, DOT).

The availability of the above capabilities is incrementally beneficial. However, even more importantly, they enable shifts in work flow which can be game-changing.

From an economics point-of-view, today, civil infrastructure has the characteristic that the consumer of transportation has zero cost access. With no market cost model, there is neither a way to match demand and supply, nor any method for building market-based optimization. This leads to inefficiencies in the system and points of shortages as well as oversupply. In this paper, we build a capability that allows us to rethink the transportation system.

The main contributions of this work are threefold:

1) Adaptive and Responsive Transportation System: Enable a transportation operating system which manages shared resources and which monitors, evaluates and manages itself based on terms of network performance parameters. FPolyOS simulation platform provides open interfaces for the implementation of new features such as advanced ride-sharing and routing protocols.

2) Market based optimization of the transportation network: The current infrastructure of the transportation systems uses the “peak capacity utilization” as the main determining factor for design and service. In this paper, we propose a “demand-supply” structure that views the transportation network as a market and uses the demand in the market with quality of service parameters such as trip time for the economic optimization. This can be modeled in FPolyOS.

3) Adaptive micro-scheduling and micro-payments: FPolyOS can model V2V and V2I communication to provide micro-scheduling and micro-payments that will allow the utilization of incentives in the system.
Adaptive micro-decisions are going to replace the static, coarse grained decisions in the traditional transportation systems.

The remainder of this paper is organized as follows. Related work is given in Section II. The system model and a detailed description of the approach are given in Section III. We present the implementation details and simulation examples in Section IV and finally conclude in Section V.

II. RELATED WORK

The idea of using electronics infrastructure to manage traffic has already started. In 2003, the City of London famously introduced a congestion charge which was enabled by electronic tolling technology [3]. Major metropolises such as Singapore have looked at similar schemes. Much academic research, led by Prabhaker [4], has looked at the incentive structure to “nudge” changes in behavior.

Computer networks and operating systems resemble the transportation system. Operating systems manage the usage of shared resources while computer networks manage the movement of data. Since the 1980s, billions of dollars of investment has gone into the development of algorithms. One of the key innovations has been new software defined network (SDN) architectures which have been developed to quickly reconfigure networks [5]. This setup enables the underlying infrastructure to be abstracted for applications and network services. There is a great deal of work on methods/policies to minimize latency while maximizing bandwidth for heterogeneous traffic patterns in the area of computer networks [6] and operating systems [7]. To date, this work has not been applicable to transportation because of the level of control available to transportation engineers. However as the level of control rises, an increasing number of these techniques will be applicable and the massive investments from these fields can be applied to transportation.

The electric utility industry has a very similar paradigm as transportation. In the power grid, the consumer expectation is to get instantaneous access to power. From the power grids point-of-view, the efficiency of the grid rises with load and at a certain point becomes inefficient/browns out. To avoid this situation, most utilities in the past would operate at a lower load/inefficient point, but this is a very expensive. Thus, the concept of demand response [8] was invented. In this concept, the system is operated closer to its optimal efficiency point. As demand rises, pricing signals are sent to modulate demand. In general, utilities work directly with large commercial clients and with consumers through smart metering programs.

The automotive industry is rapidly adopting new revenue streams including shared mobility and data connectivity services [9]. In the area of market pricing, Uber runs a “surge” pricing concept where pricing reflects the demand/supply dynamic [10]. The focus of the pricing model is to encourage supply based on market demand and the system is effective in providing capacity into the Uber system.

Overall, many individual aspects of the proposed FPolyOS have been proven to be successful in other fields. However, only a small portion of these approaches is employed, and only in isolation, for the transportation system. In this paper, we propose to pull it together and create a system for modeling and analyzing system-wide solutions.

III. FPOLYOS

In this section, we first describe the engagement models for FPolyOS to emphasize the motivation of the particular design characteristics. Then we provide the details of the design, implementation and important features for the proposed system.

A. Engagement Models

The FPolyOS will provide us the knobs to use network parameters for optimization and account for mass traffic effects. The underlying electronics infrastructure enables quite interesting top-down economic and engagement models. We envision some of the scenarios with the full understanding that all have policy implications to be handled:

- **Latency Minimization:** Mary needs to go to her job interview urgently. Through her mobile app she indicates her desire and a budget she is willing to spend. Through V2V communications, her car pays cars ahead of her to give her right of way. Through V2I communications, smart traffic lighting systems favor Marys route when it is possible and create an additional source of tax income.
- **Bandwidth Optimization:** Judy, the traffic engineer, manages a very important road segment. She knows that the density of traffic can rise to a certain point for smooth flow, but after that point the roads efficiency drops rapidly. As the density rises, Judy releases credits available to the network of people who want to use this segment to modulate demand into the road network.
- **Reverse Metering:** Alvin is a retiree. He wants to go shopping but has no special preference of time. He registers his desire to shop in a certain band of time and his application tells him the best time to go. Sometimes he can even earn some credits for going in certain zones of time.
- **Transportation Business Planning:** Fred runs the department of transportation operations to decide where to invest resources to expand or build new civil infrastructure. In the old days, he would look at traffic congestion snapshots and projections of future growth. Now, he not only has the data for whole trips, but also the economic desire for each trip. With this information, he can make an economic argument for expansion and the return on investment can be modeled directly. Given the direct connection to expected revenue, Fred can much more easily justify projects.
- **Commercial Applications:** Elane runs a commercial trucking company. For her e-commerce customers, latency is critical and they will pay for it. For those trips, she allows her drivers to pay additional tolls through the micro-tolling infrastructure. For her non-e-commerce customers, timing is not so important as long as the goods get there in time. Also, these customers are super focused...
on cost. For these trips, she moves the freight to off-peak times when the cost of the infrastructure is low.

- Emergency Vehicles: Danny is an emergency medical technician. In the past, getting to the hospital was tricky as he tried to navigate traffic signals which were against him. Now, when he turns on his siren, the traffic lights automatically turn in his favor and the cars ahead of him give him right of way.

### B. System Architectural Model

Changing a multi-trillion dollar industry will not happen overnight. In addition, to introduce many of the ideas given in engagement models, there are countless policy, consumer response, and availability of infrastructure considerations. In order to understand this situation, there is a need to build a simulation framework which can model the critical aspects of this environment. Specifically, the framework must provide support for the following:

- Real-World Infrastructure Topology
- Real-World Traffic Patterns
- Directed agents (fleets or AVs)
- V2V and V2I communication
- Cellular (5G) communication with cloud management
- Market pricing and policy strategies

Using an environment with the properties above, it is possible to take realistic scenarios and model the development, investment, and deployment of the systems that will provide the engagement models. An architectural overview of the FPolyOS is given in Fig. 1. The layered architecture separates control functionality from physical communication based functions.

![FPolyOS architecture](image)

The first layer in FPolyOS architecture is the simulation platform, which provides capabilities required for intelligent transportation system modeling. These capabilities include conventional transportation modeling features such as traffic simulation, street network design, signalization modeling, trip creation and so on. In addition to these conventional capabilities, FPolyOS adds V2X communication modeling and provides the capability to augment agent behaviour based on inputs from the operating system.

The second layer of FPolyOS architecture serves as the Operating System of the transportation network. This layer uses the collected data from transportation units to abstract and maintain network state information. The abstract system information is provided to the layer above through open interfaces. This structure provides a global understanding of the system and allows various protocols and algorithms to be created using the collected data.

The top layer of FPolyOS is the Application Layer. The operating system below this layer and its interfaces provide opportunities to develop control applications for the transportation system such as micro-tolling, smart routing or traffic load balancing. One of the important applications which can be built are global resolution functions such as a local marketplaces which use algorithms similar to stock exchanges.

With the separation of concerns, the FPolyOS allows for independent software development and a high degree of reuse. As an example, existing software packages from the transportation sector can be used at the bottom layer while next-generation software packages can be integrated from the world of networking/operating systems in the operating system layer. Finally, the highest layer can leverage the work from many industries to build and test unique optimization points while sourcing software from fields such as economics.

FPolyOS was created to make it much easier for transportation agencies to prepare to imagine, pilot, and deploy a range of capabilities (Demand Response, microtransit, or Mobility-as-a-Service) with reduced risk and enhanced understanding of potential outcomes under complex demand and service scenarios.

### IV. Implementation Study

In the world of demand response, the first manifestations consisted of utilities working with commercial clients to shift electricity usage demand. With that in mind, we setup a proof-of-concept study for FPolyOS where we considered the impact of shifting the time of day at which freight used the transportation system. To make it realistic, we used extensive data from Berlin [11]. This experiment provided an opportunity to test the applicability of FPolyOS architecture for a realistic transportation study. In the next section, we describe the construction of the simulation platform, test cases we used to drive the simulation, and finally, the results of the study.

#### A. Abstracted Simulation Software Layer

The overall implementation framework is given in Figure 2, and it maps the FPolyOS architecture given in Figure 1 to the implementation in practice.

For the bottom layer, we used MATSim [?] as the simulation platform since it already has the transportation modeling capabilities we aim to use as well as it has features that allow us to implement important future techniques such as CAV technologies. To this base simulation, we added Via for scenario visualization, OpenStreetMap (OSM) [12] for map
data import, Java OpenStreetMap (JOSM) for converting OSM files to MATsim network files, and custom Python scripts to generate statistics from the raw output of MATSim event files.

We overlaid the Simulation Environment Layer with a programmable control layer to develop the Operating System layer. Parameters such as average trip duration, street usage, and average vehicle speed are abstracted for application use in the top layer.

To enable our experiment, we built two custom modules: Trip Generation Module and Link Analysis Module. Trip Generation creates a path for an agent by collecting all the possible destinations nodes (called facilities) that a certain archetype might want to visit and then randomly generates a different destination from the facilities that are available to that archetype. Duration spent at those facilities varies for each archetype’s purpose. This allows simulation model designer the capability to create multiple plans with the click of a button instead of arduously coding them in the simulation platform.

Link Analysis Module also allows us to visualize link usage. The module works by keeping a running total each time an agent enters each link. Without this module, the main parameter used to optimize the system was time, such as travel time or time spent in traffic. The Link Analysis Module provides us with another valuable metric for optimization, Traffic Distribution. The Link Analysis Module provides our team with a finer grain metric to understand and analyze different traffic situations and routing algorithms.

On the Application Layer, we built a dynamic network manipulation application and a smart shifting application. The purpose of the dynamic network manipulation application is to dynamically change the network in a manner that it would simulate changes to the traffic flow such as blocking the road, changing the lane capacity, and changing the lane speed.

To evaluate the capabilities of FPolyOS on creating an adaptive and responsive transportation system environment, we also developed a traffic shifting application, which uses the traffic information collected in the simulation environment layer and abstracted at the operating system layer. The main goal of the application and related simulations is to demonstrate the utilization of the abstract information from lower layers for exploring new concepts in the system.

B. FPolyOS Test Cases

Figure 3 shows Poly City, a small transportation system, created in the simulation platform. Poly City functions as our test-bed, where what-if scenarios and new features can be implemented and tested within short simulation time for fast iterative development. Using Poly City accelerates implementation and testing of custom modules for the FPolyOS.

For example, to verify that the Dynamic Network Manipulation Application works, we used our Link Analysis Module at the Operating System layer to communicate with the simulation platform and use the information related to the real-time road usage.

Figure 4 shows an example for Dynamic Network Manipulation Application in PolyCity, where Control represents the city on a regular day and Modified represents the city with accidents. A regular day represents a day the city is functioning normally and that no links are blocked. Whereas in the modified simulation, links 103 and 127 are blocked due to an accident. The link speed becomes 10% slower each minute for 4 minutes. Then, at around the 8 minute mark the link is blocked altogether. As shown in Figure 4, shutting down link 103 and 127 causes the usage of those links to drop significantly, As a result, the cars were rerouted causing other links usage to spike up.
To evaluate FPolyOS in a large transportation system, we also incorporated an existing open-source city model, the MATSim Berlin transport model [11], provided by the Transport Systems Planning and Transport Telematics group of Technische Universität Berlin. The Berlin model includes approximately 10,000 nodes and 30,000 links. In addition to a dense network, Berlin has an extremely rich set of input agents. Most importantly, all of this data rich information had already been converted into MATSim, which give the team a pre-built city to manipulate. The collected data used to create agents includes Germany’s 2011 Zensus, General Transit Data for bus systems, local traffic, freight traffic, and so on. Although using all of this data would be ideal, the data was so massive that we used 1% of the data for testing our theories and 10% of the data for simulating on a large scale. Our 10% simulation results are depicted in Figures 6 - 8. A snapshot of Berlin simulation is given in Figure 5.

C. Freight Shift Berlin Experiment

As the experimentation test, we chose the arrangement of freight traffic in the city. The application allows timing change of freight traffic through its programmable interface. Hence, we explored how FPolyOS can be used with this application to explore the effects of traffic shifting on the number of vehicles on the road during peak hours.

The application applies two different types of algorithms, ‘Basic’ and ‘Smart’ shifting, on a selected group of vehicles for rescheduling. All of our ‘Basic’ algorithms work by iterating through the travel plans of all agents in the system and randomly selecting plans such that n% of the overall number of plans were modified where n is 2, 5, and 10. Then each plan was shifted forward by selecting a number around the shift amount such that a normal distribution was formed. Our ‘Smart’ algorithm worked similarly except it shifted traffic between 7 AM and 9 AM to 5 hours earlier and traffic between 4 PM and 6 PM to 5 hours later. By using these algorithms we were able to get a basic understanding of what percentage of traffic and how much it needs to be shifted to have a large impact on the experience of an individual agent.

Figure 6 shows the results of our shifting algorithms when applied to 2% of all agents in the city. The figure clearly shows that the difference between the control and the 3 hour shift is negligible while the 5 hour shift and the 8 hour shift are beginning to have a large impact on the number of cars on the road during peak hours.

Figure 7 shows the results of our shifting algorithms when applied to 5% of all agents in the city. In these results, an obvious separation between the results of different algorithms can be seen. While the 3 hour shift has a slight difference compared to the control line, the 5 hour smart shift and the 8 hour shift have begun to noticeably deviate from the control.

Figure 6. 2% Non-freight Chart for the four different shift types

Figure 7. 5% Non-freight chart for the four different shift types

Fig. 5. Large transportation system simulation scenario

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something significant, the result may well be interesting. Various fleets (school busses, city maintenance, trucks, etc.) to 10% has an immediate impact. If one could cobble together the percentage of freight traffic. If the percentage is low, the peak times improves the situation, the answer depends on questions.

The simulation results show that FPolyOS provided the necessary dynamic environment to develop an application for exploring the effects of a transportation system change. This can be invaluable for a transportation system planner in decision making process. The simulation results also show that the interfaces that we provide between MATSim, our system modules, and the programs are developed enough to test real questions.

On the actual question of whether shifting freight to off-peak times improves the situation, the answer depends on the percentage of freight traffic. If the percentage is low, the impact is muted. However, the study shows that only going up to 10% has an immediate impact. If one could cobble together various fleets (school busses, city maintenance, trucks, etc.) to something significant, the result may well be interesting.

V. CONCLUSION

The injection of technology from the electronics industry is poised to revolutionize the transportation industry. There is a great deal of outstanding work ongoing in areas such as autonomous vehicles. However, the transportation infrastructure can also be revolutionized with these technologies and in fact, fundamentally new use-models can be enabled. To invent, study, and deploy these use-models, there is an intense need for a simulation platform to understand the ramifications.

We present FPolyOS, a simulation environment designed to explore opportunities in transportation system enabled by bottom-up electronics infrastructure. FPolyOS has a layered architecture with control planes, which allows the creation of novel applications for the transportation system using open interfaces. This means that applications can be consumed from the traditional transportation industry, they can include applications from computing, and extend to software from fields such as economics. In this initial version, we focused on exploring concepts such as market based optimization in traffic, adaptive micro-decision implementations and fine-grained management of freight and logistics.

As future work, we plan to develop a market-based optimization solution for specific areas in Florida. Hence, we have obtained access from the Florida Department of Transportation (FDOT) and received API level access to the Florida Advanced Traveler Information System (FL-ATIS), which provides traveler information throughout the entire state. FL-ATIS data will be used to create a realistic model of the application area and implementation results will be compared to the existing conditions.

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