CS426: AGENT-BASED MODELING AND SIMULATION

PROF. SHIH-FEN CHENG

G1-T07

Final Report

Environmental Effects of ERP Congestion Charges

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Abstract

This project explores the environmental implications of congestion charges, focusing on whether they inadvertently increase pollution by diverting traffic to arterial roads. Using agent-based modelling, we simulate traffic patterns and analyse the effects of congestion charges for different infrastructure scenarios. Our findings reveal a nuanced relationship: while congestion charges initially reduce CO_2 emissions by easing expressway congestion, excessive congestion charges and additional traffic lights on arterial roads can worsen emissions due to increased idling and traffic oscillations. We subsequently conclude that optimal pricing and infrastructure management is critical to minimising environmental impact.

Introduction

The introduction of a congestion charge on expressways (known as the Electronic Road Pricing (ERP) System in Singapore) has often been lauded for its ability to alleviate peak-hour traffic congestion and improve traffic flow, but its unintended consequences on environmental pollution have become a growing concern. Although some road users may be deterred from using expressways with congestion charges, this does not necessarily lead to less traffic overall as commuters often opt for alternative routes by travelling on arterial roads with traffic lights – leading to an increase in stop-and-go traffic and greater distances travelled. Hence, our project seeks to answer a critical inquiry: do congestion charges inadvertently contribute to more environmental pollution by diverting traffic?

Using the agent-based modelling and simulation (ABMS) approach, we created a simulated environment where our agents (road users) dynamically interact with one another and their surroundings. This enabled us to observe emergent patterns which proved to be valuable in deriving insights into how congestion charges influence traffic patterns and environmental pollution. In our evaluation, we ran the model against various scenarios to explore the effects of different congestion charges, infrastructure changes (i.e. traffic light timings) and decision-making strategies.

Literature Review

We conducted a multi-faceted review of existing academic research to devise a nuanced approach for our model. This was done in a 3-pronged approach — we first identify studies relating to Singapore’s ERP system, then expand our search to understand the observed environmental effects of congestion charges and before model implementation, verify the correctness of the magnitude of our parameters through corroboration.

Literature on Singapore’s ERP System

In the first component of our review, it was observed across several studies that peak period road pricing tends to transfer congestion to other periods and other routes. However, this is generally less serious than the congestion which existed before (Olszewski & Xie, 2005). It was also noted that the Land Transport Authority (LTA) conducts quarterly travel speed reviews to adjust charges to yield targeted speed ranges of 45 to 65 kph for expressways, and 20 to 30 kph for arterial roads. These speed ranges were set based on the engineering capacities of the expressways and arterial roads, respectively, and correspond mainly to traffic flow near capacity with vehicles unable to change lanes because there are few usable traffic gaps (Phang & Toh, 2004). We will use these benchmarks and behaviours during our verification and validation process to ensure both the model's correctness and robustness.

Literature on Environmental Effects of Congestion Charges

When it comes to the research done on our subject of interest, extensive research has been conducted in many other cities with congestion charge systems. We reviewed research mainly from London and Stockholm but also included feasibility studies from other transport-centric think tanks, such as the Victoria Transport Policy Institute based in Canada. During the review, it was ascertained that congestion charges do in fact reduce environmental pollution — be it through traffic deterrence, or reduction in traffic oscillation (Daniel & Bekka, 2000). However, it was noted that in the case of London, environmental pollution in surrounding areas increased as a result (Percoco 2015). These observations provided a glimpse into possible insights into our hypothesis but were not definitive as the systems were different in implementation — both London and Stockholm used the concept of Restricted Zone (RZ) where all points of entry to the city were chargeable but in Singapore, charges were only applicable to certain expressways and arterial roads; making travel to all destinations still possible through alternative routes.

Literature on Model Parameters

This last segment of our review was focused mainly on fixed (non-configurable) model parameters which were paramount to an accurate simulation – they include (but are not limited to) the utility values assigned to each action of an agent (when deciding between routes using fictitious play) and the greenhouse gas emission rates per unit distance travelled. When it came to deciding how the utility of expressways can be penalised with respect to congestion charges, it was revealed by Senior Minister of State for Transport Josephine Teo that speeds rose an average of 7 per cent per dollar increase (Toh 2020). For the latter, the average emission rate for cars travelling and idling was also adopted based on 2 different papers, namely from the Intergovernmental Panel on Climate Change and the United States Environmental Protection Agency (IPCC 2006; USEPA 2008).

Hypothesis

The use of congestion charges on expressways contributes to more overall environmental pollution by diverting traffic to arterial roads during periods of traffic inelasticity (i.e. during peak hours). We anticipate that traffic lights will play a significant role in creating stop-and-go traffic, which worsens congestion and generates more greenhouse gases as vehicles accelerate more and idle longer.

Model Description

While the logic behind our simulation is elaborate, we built the model environment based on Occam's Razor principle, providing a simple space for agents to interact in. We abstracted the choices drivers would make into 2 main decisions – either take the expressway or the fastest arterial road route. This eliminated the need for advanced pathfinding algorithms or complex road networks as we could focus more on modelling realistic driver behaviours. There are several fixed parameters in the code, which are non-configurable as they either reflect the empirical observations made in the real world or prevent agents from deviating too far away from collective behaviour; these variables are the driving and idling emissions of vehicles, the utility penalty of congestion charges and the percentage variation of both agent speed and acceleration/deceleration. We took a balanced approach in giving certain observations more weight (i.e. by modelling them into the simulation) and others less (i.e. by either simplifying or omitting them) depending on their relevance to our goal. This is explained in the subsequent subsections in more detail.

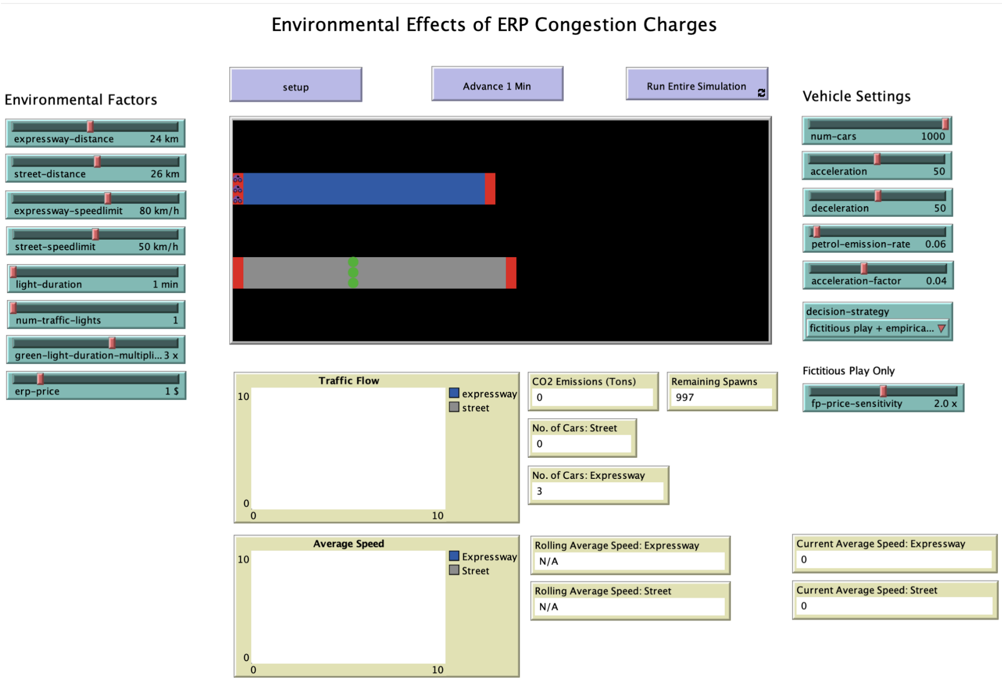


Figure 1: NetLogo Model Interface

The Environment

The roads are modelled to represent 1 kilometre per unit patch, with the blue patches representing the expressway and the grey counterpart representing the arterial road. The red patches at the start and end of both roads are indicative of the start and end points; cars that pass the endpoints will “die” or disappear from the environment as they have reached their goal. Every tick during the simulation represents a minute, and each agent represents a single car. For the purpose of our model, there are only 3 lanes for both roads and we assume that lane changes do not happen as they have been factored in average speed calculations. As cars travel along their route, it is possible that some agents may wish to exit the expressway or arterial roads to an earlier destination – this is modelled as a dropout rate of 1% and 5% respectively for each minute as a simplification.

The Agent

The main agents present in this model are the individual cars, which move through our abstract environment from their point of origin on the left to their final destination on the right. During the transit, these agents have unique top speeds which are varied randomly based on the speed limit to simulate road users of different competencies (i.e. novice drivers may drive under the limit, while veterans may choose to speed). In addition, they dynamically adjust their speeds to avoid collision with one another, with a probabilistic acceleration and deceleration to simulate traffic oscillations (i.e. drivers may engage the brake harder than the car in front of them). On arterial roads, the traffic lights are modelled as another type of agent which when red, causes all cars in front of them to stop.

The main power of this model comes from the decision-making as to which road the cars choose to take. This decision is made before the cars spawn into the model environment and it is important to note that in this context, the idea of a “decision” and “utility” do not fit perfectly into the game theory framework we have seen in class. This is because the game being played between drivers here has an added time dimension: drivers who enter the road later can see how fast traffic has been moving previously, as well as how full each path currently is. Additionally, the utility a driver receives (the speed they travel at) is based on the physical simulation of them moving through the environment, which varies throughout the simulation as the traffic flow changes.

The decision can be made in one of two ways, depending on the option selected by the decision-strategy chooser. In the proportional probability method (which is a simplistic application not representative of road user behaviours), cars randomly choose between the street and the expressway in proportion to the ERP cost, with a 5% chance of choosing the expressway when the ERP price is \$6, and a 5% chance of choosing the street when the ERP is free (\$0). This is purely to demonstrate the randomness associated with our model and assumes that drivers are purely sensitive to prices in the linear fashion which we know to be not true.

Hence in our fictitious play option, driver behaviours are modelled based on a real user story – before travelling to its destination, a driver would look at the traffic situation on his/her smartphone over the past few minutes and identify certain key decision-making factors such as the price of the ERP charge and the rolling average speed of cars already on the roads. We then model our fictitious play strategy based on perceived utility derived from our Literature Review, combining the current average speed with a penalty modifier to model the expected utility payoffs of each road. The true payoff would then be the actual speed of the agent during the transit, which is added and averaged over all agents currently travelling on a road at a single point in time.

Model Parameters

Aside from the fixed model parameters mentioned above, the table below summarises the variable model parameters available on the UI:

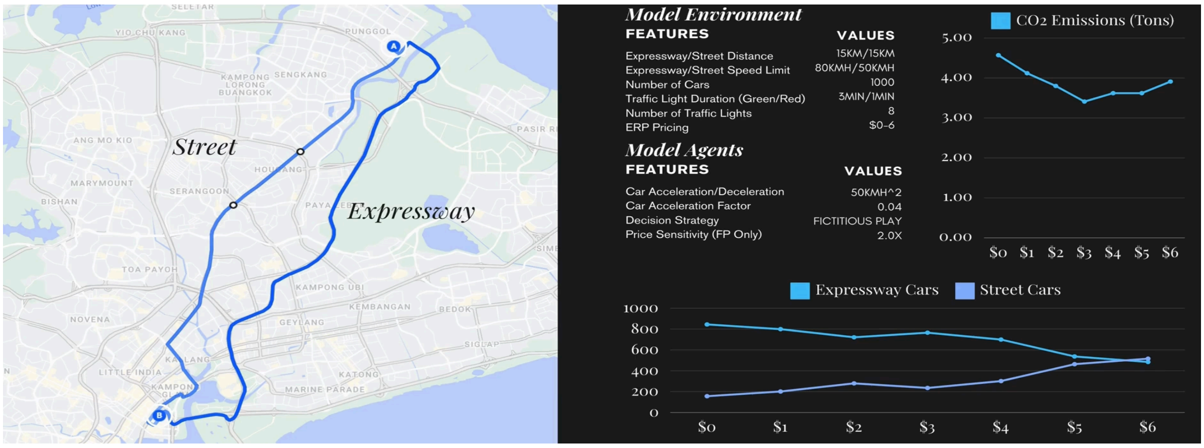
Model Environment	Model Agent
Expressway/Street Distance Expressway/Street Speed Limit Number of Cars Traffic Light Duration (Green/Red) Number of Traffic Lights ERP Pricing	Car Acceleration/Deceleration Car Acceleration Factor Decision Strategy Price Sensitivity (FP Only)

Table 1: Variable Model Parameters

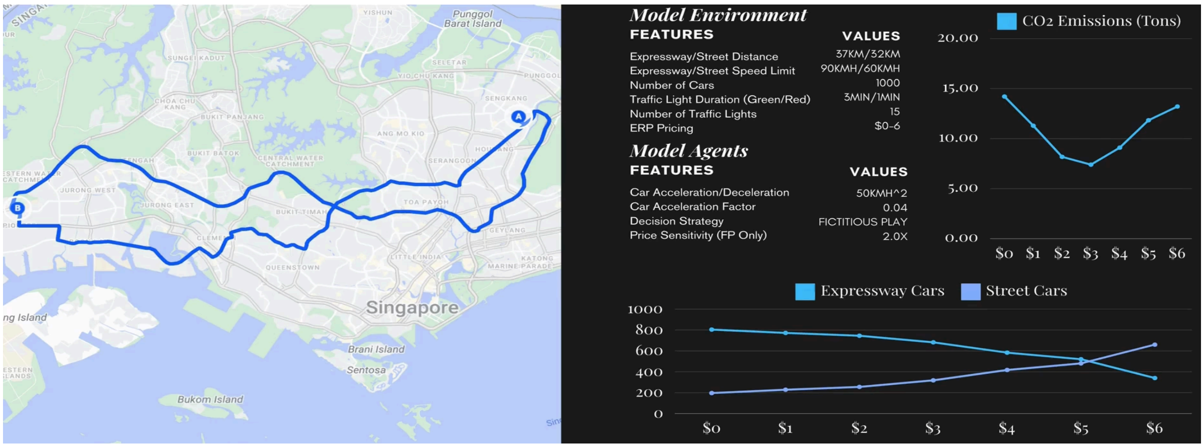
The specified parameters in the table come in the form of sliders on our interface, allowing users to model different scenarios based on empirical data. Specifically, the distance, speed limits (for the two road types), and number of traffic lights are meant to be adjusted to match a real-world scenario. This can be done by finding a route from one part of the city to another using an external map application, then adjusting the distances and other information (if available) according to requirements. In addition to the inclusion of a decision strategy dropdown menu which allows for new behaviour models to be considered in the future, a multiplier for price sensitivity is also provided to fine-tune the model depending on the overall economy – for instance, road users will be more sensitive to an increase in congestion charges during a financial downturn which would cause traffic patterns to deviate.

Results

Our study conducted simulations based on real-life scenarios, focusing on two routes: one between Punggol Park and Suntec City, and the other between Punggol Park and Singapore Discovery Centre. Through BehaviorSpace experiments, we varied ERP pricing and aggregated data over 100 iterations, enabling the calculation of average CO2 emissions in tons.



Scenario 1: Punggol Park – Suntec City



Scenario 2: Punggol Park – Singapore Discovery Centre

Effect of Congestion Charges on CO2 Emissions:

- Introduction of a congestion charge initially led to a reduction in CO2 emissions, indicating decreased congestion within expressways.
- However, a subsequent increase in ERP prices beyond a certain threshold resulted in elevated emissions. Further analysis uncovered that the combination of traffic lights and increased ERP prices contributed to prolonged idling periods and exacerbated traffic oscillations, causing abrupt stops in traffic flow.

Impact of Distance and Traffic Lights:

- The second scenario, covering the longer distance between Punggol Park and SDC, highlighted a more significant variance in CO_2 emissions.
- With additional traffic lights along the route, the potential reduction in CO_2 emissions approached nearly 50% when ERP pricing was optimised.

Key Takeaways

- Congestion charges effectively reduce congestion within expressways and, consequently, CO_2 emissions up to a certain level. However, beyond a specific ERP price threshold, emissions may rise due to increased idling and traffic oscillations.
- An ideal balance between cars on expressways and arterial roads is crucial to minimise traffic oscillations, thus reducing CO_2 emissions.
- While traffic lights may contribute to traffic oscillations, they also serve to reset traffic flow, mitigating their adverse effects and reducing overall CO_2 emissions.

Verification & Validation

With reference to the section above regarding “Literature on Environmental Effects of Congestion Charges”, the research conducted on London’s Congestion Charge verifies the phenomenon of increased environmental pollution due to traffic diversions and increased distance travelled. We also observed that the global minimum for CO_2 pollution is achieved in our model when the average speed of both route options is maximised (which is directly attributed to the reduction in stop-and-go traffic). These results align with research published regarding the increased fuel consumption from traffic oscillation by both congestion and mandatory traffic light stops (Li X., Cui J., An S. & Parsafard M, 2014).

Further Exploration

This model could be improved in a variety of ways with additional time and resources. We could increase the detail and provide a more accurate simulation through empirical data collection and the inclusion of more nuanced features. For instance in the agent aspect, we can make the roadways more realistic by adding lane change logic, granular speed limits or even vehicular accidents. We could also improve the environment aspect by modelling time-based ERP charges (with accompanying traffic variability). It may also be prudent to simulate congestion charges which only apply to specific vehicle types (i.e. Diesel etc.), which would allow better policy-making decisions from the transport authority with environmental impact in mind.

Figure 2: Example of GIS Data in NetLogo

A more ambitious extension of this project would include GIS data in NetLogo to accurately simulate traffic flows based on actual roads in Singapore. This would require significantly more processing power but may provide better accuracy especially for our exit rate logic, which is dependent on egresses available to an agent when travelling on a roadway.

Conclusion

Based on our findings, we conclude that the answer to our hypothesis is more nuanced than originally thought. The introduction of congestion charges does in fact reduce overall environmental pollution but it also exacerbates overall environmental pollution depending on the pricing strategy applied. The relationship is parabolic in nature, with the global minimum representing the ideal congestion charge to minimise environmental pollution. However, this relationship is unique to every traffic scenario so each ERP gantry around Singapore would require its own evaluation. It was observed that traffic lights did not play as significant of a role in worsening congestion, as they played an equal role in alleviating congestion by resetting traffic oscillations when vehicles stopped. This phenomenon cancels out the additional emissions caused by idling as vehicles do not accelerate as often. Overall, our hypothesis only holds true in circumstances where congestion charges are “overpriced” and while traffic lights did create stop-and-go traffic which significantly reduced average speeds, it did not generate additional environmental pollution to warrant its effect as substantial.

Acknowledgements

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References

Olszewski, P., & Xie, L. (2005). Modelling the effects of road pricing on traffic in Singapore. Transportation Research Part A: Policy and Practice, 39(7–9), 755-772. https://doi.org/10.1016/j.tra.2005.02.015

Phang, S.-Y., & Toh, R. S. (2004). Road Congestion Pricing in Singapore: 1975 to 2003. Transportation Journal, 43(2), 16–25. http://www.jstor.org/stable/20713563

Litman, T. (n.d.). Road Pricing. TDM Encyclopedia. Victoria Transport Policy Institute. Retrieved from https://www.vtpi.org/tdm/tdm35.htm

Percoco, M. (2015). Environmental Effects of the London Congestion Charge: a Regression Discontinuity Approach.

Daniel, Joseph & Bekka, Khalid. (2000). The Environmental Impact of Highway Congestion Pricing. Journal of Urban Economics. 47. 180-215. 10.1006/juec.1999.2135.

Toh, T. W. (2020, January 7). When ERP rates rise, traffic speed goes up too, says Josephine Teo. The Straits Times. https://www.straitstimes.com/singapore/transport/when-erp-rates-rise-traffic-speed-goes-up-too-says-josephine-teo

Intergovernmental Panel on Climate Change. (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Volume 2 Energy. IPCC National Greenhouse Gas Inventories Programme. https://www.ipcc-nggip.iges.or.jp/public/gp/bgp/2_3_Road_Transport.pdf

Vermont Department of Environmental Conservation. (2008). Idling Emissions Reduction Program: A Guide for Municipalities. Retrieved from https://dec.vermont.gov/sites/dec/files/aqc/mobile-sources/documents/IdlingEmissions.pdf

Li, Xiaopeng & Cui, Jianxun & An, Shi & Parsafard, Mohsen, 2014. "Stop-and-go traffic analysis: Theoretical properties, environmental impacts and oscillation mitigation," Transportation Research Part B: Methodological, Elsevier, vol. 70(C), pages 319-339.