Traffic dynamics of multiple paired U-turn slots

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Abstract

A particular road configuration involves multiple U-turn slots. We show the conditions needed to construct the same scenario using a system of paired U-turn slots as the building block. Clogged states are determined for different separation distances between opposing U-turns. For the same distance travelled, a car on a road with less U-turn slots will spend less time than one on a road with more slots. The latter road configuration is only more favored for cars that make a turn early.

Keywords: Traffic, median U-turn, lane-changing

1 Introduction

U-turn slots are used to eliminate the need for left turns, and see wide use on some roads in Metro Manila. Vehicles choose where to make a U-turn among multiple slots depending on the conditions or destination. However, traffic at high demand can be overwhelming as indifferent drivers want to ensure a turn and compete against each other for an opportunity at the nearest slot, or if not possible at the next nearest free one. The driver decides between waiting for a congested but near U-turn slot to free up or opting for the less congested ones at the cost of greater travel distance.

Existing studies on U-turn traffic have laid out the dynamics on single median U-turns. One finding showed that free flow is only achieved at low car inflow [1]. Other studies [2, 3] focus on measuring U-turn capacity particularly influenced by the critical or merge gap which is the acceptable time for an incoming on-ramp vehicle to reach a vehicle from the U-turn before the latter merges with the on-ramp traffic.

A problem in constructing multiple U-turn slots is determining the optimal separation distance. One of the significant findings in [4] is the occurrence of clogging where a queue of cars trying to make a turn on two opposing U-turn slots block one another and form a gridlock. A short separation distance between these two U-turn slots could increase the chances of clogging, thus lowering U-turn flow capacity. On the other hand, long separation distance could accommodate greater flow but incur longer travel time.

In this study, we simulate a similar scenario using the developed U-turn system in [4] as building blocks and present the conditions to construct a scalable version. We also identify when clogging occurs and the time delays cars experience for different separation distances.

2 Methodology

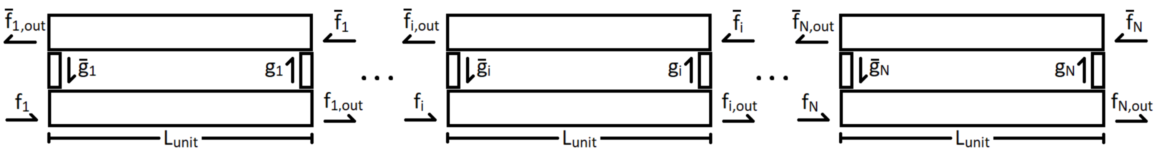

Figure 1: N-chain system. Arrows indicate direction of traffic flow at segments of each unit cell. Corresponding flows on the opposite side of the road in each unit cell are labelled with bars.

Let a system of paired U-turn slots be a unit cell (Fig. 1 middle) with inflow rate f_i, outflow rate $f_{i_{out}}$, probability p_{u_i} for a spawned car to want to make a turn, and length L_{unit} as the separation distance between the opposing U-turns. The resulting flow rate g_i at a U-turn slot is mainly influenced by p_{u_i}. The corresponding opposite flows are labelled with bars. This unit cell is based on [4] where traffic is simulated using a cellular automata model and a road is represented by a $3 \times L_{unit}$ lattice. A car occupies a single lattice cell (not to be confused with the unit cell) and can move with velocity v ranging from 0 to $v_{max} = 5$. As a real-world reference, simulation timestep = 1.8s and lattice cell length = 5m [1], so v_{max} = 14 m/s or 50 kph. Cars wanting to make a turn will assertively go to the two inner lanes to ensure a turn while non-turning cars will want to move to the outermost lane. We build a scalable system by concatenating N unit cells for a total length of $L = NL_{unit}$. We explore the feasibility to realize the N-chain system while relying only on the properties of a single unit cell. This would however introduce constraints on parameters and limit the analysis only to turning cars that have the same origin and destination which is either of the edge unit cells. Considering varying destinations would require a full simulation of the N-chain system.

The outflow rate $f_{i_{out}}$ of the ith unit cell, contributed by the inflow rate f_i and the two U-turn flow rates g_i and $\bar{g}_i$

$$f_{i_{out}} = f_i - g_i + \bar{g}_i \tag{1}$$

and the inflow rate f_{i+1} of the following unit cell $i+1$ must be conserved:

$$f_{i+1} = f_i - g_i + \bar{g}_i \tag{2}$$

$$\bar{f}_i = \bar{f}_{i+1} + g_{i+1} - \bar{g}_{i+1} \tag{3}$$

Imposing symmetric inflow and U-turn flow on each cell

$$f_i = \bar{f}_i \tag{4}$$

$$\bar{g}_i = g_i \tag{5}$$

then the parameter constraint is that the inflow rate and outflow rate of a cell must be equal

$$f_{i+1} = f_i \tag{6}$$

$$\bar{f}_i = \bar{f}_{i+1} \tag{7}$$

We calculate the time delay of the ith unit cell

$$\Delta t_i = \frac{1}{v_i} - \frac{1}{v_{max_i}} \tag{8}$$

where v_i is the mean velocity on the road at steady state and v_{max_i} is the maximum velocity for that cell, which is the extra time a car will spend on average over a unit distance compared to when it is at free flow.

For the simulation the total length L is set to 400. So that a whole number of unit cells is used, only factors of 400 are assigned to L_{unit}. Effective inflow and outflow rate measurements are conducted to verify validity of the N-chain system approach. Once verified, the total time delay

$$\Delta t_{total} = \sum_i \Delta t_i \tag{9}$$

is calculated for different p_{u_i} combinations and different number of units cells traversed on $L_{unit} = 100, 200$.

3 Results and Discussion

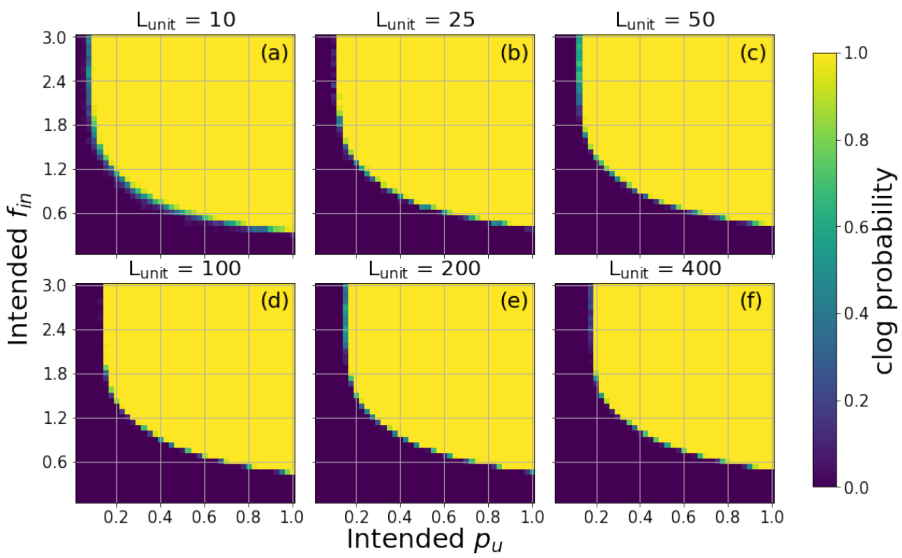

Figure 2: Clogging probability of the two inner lanes in the $f_{in} \times p_u$ space for the following L_{unit} values: (a) 10, (b) 25, (c) 50, (d) 100, (e) 200, and (f) 400.

Clogging in a unit cell occurs when the inner lanes on both roads and the two opposing U-turns are fully occupied by turning cars, forming a gridlock. It is necessary to identify traffic conditions that trigger clogged states as a measure of the turning capacity — how many cars a unit cell can allow to make a turn. For a particular f_{in} and p_u, the probability to clog is approximated by the fraction of realizations in the simulations that it occurred. Figure 2 shows the clog probability diagrams for values of L_{unit} that are factors of $L = 400$. Each diagram shows the number of unclogged states decreases as f_{in} increases.

The region of clogged states (probability equals 1, color yellow) decreases as L_{unit} increases. Longer separation distance provides a lower chance of interaction between turning cars and non-turning cars. It also requires a longer queue of turning cars to build up in the inner lanes for clogging to occur. The decrease in area of this region however becomes less noticeable at higher values of L_{unit}, indicating that at a certain point further lengthening the road will only provide little improvement in the turning capacity.

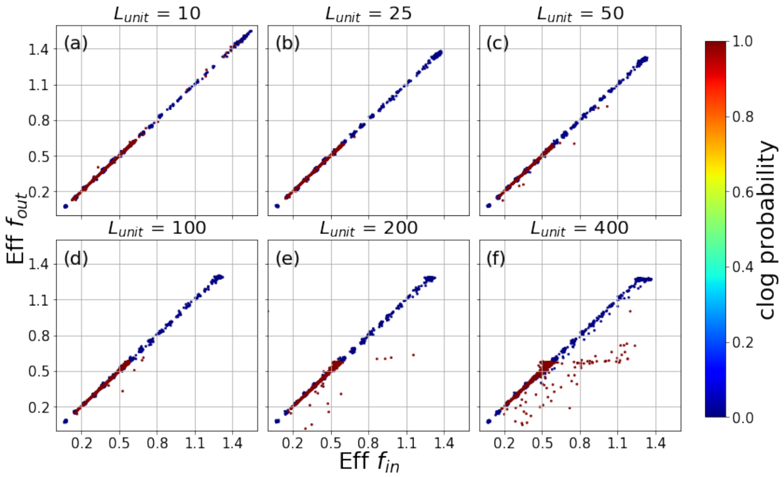

Figure 3: Effective inflow and outflow rates for the following L_{unit}: (a) 10, (b) 25, (c) 50, (d) 100, (e) 200, and (f) 400.

Car interactions due to reaching road capacity, random slowdown, and the asynchronous nature of updating car movement prevent actual traffic flow rates in a unit cell from matching corresponding intended simulation parameter flow values. Figure 3 compares the measured effective inflow rates with the effective outflow rates for different values of L_{unit}. Unclogged states (blue points) fulfill the condition of $f_{in} = f_{out}$ for the N-chain system to be constructed using the properties of a single unit cell. The clogged states (red points) occupy a smaller region of low effective values; this is because the two inner lanes in a clogged unit cell are fully occupied by turning cars and the outermost lane is the only one remaining with non-zero flow. The formation of clusters is just the consequence of discrete parametrization.

We now discuss a way to analyze the full N-chain system. As stated earlier, since flow is conserved between adjacent cells, all cells must have the same f_{in} values. If each cell is represented as a point with its intended parameter values as coordinates in the f_{in} vs. p_u phase diagram, connecting the points should trace out a horizontal line segment. The U-turn flow rate g_i on the other hand is only affected by turning car spawn probabilities p_{u_i} which are unconstrained parameters. Thus for a particular L_{unit} and f_{in}, we can construct a distribution of total time delays (Eq. 9) from different combinations of p_{u_i}. Values in the clogged region however are excluded in constructing the distribution since turning cars fail to make a turn and p_{u_i} is no longer representative of a unit cell's state. Cars stuck in the two inner lanes will experience an infinite time delay.

Distributions of the total time delays are shown in Fig. 4. For both diagrams of L_{unit}, as f_{in} increases, the distribution transforms from a single agglomeration (intended $f_{in} \leq 1.2$) into separate aggregates (4 for $L_{unit} = 100$ and 2 for $L_{unit} = 200$ which are the respective number of unit cells needed to construct a road with $L = 400$). Focusing on $L_{unit} = 100$ and a high intended f_{in}, say 3.0 (pink aggregates), upon checking the simulations the leftmost aggregate (the one with the lowest total time delays) is found to correspond to configurations where cars turn on the first U-turn slot, the next aggregate corresponds to those turning on the second U-turn slot, and so on. This means at high traffic flows, cars that fail to make a U-turn early are penalized with greater time spent on the road than at low traffic flows. The same observation can be said for $L_{unit} = 200$ and intended $f_{in} = 3.0$ where the leftmost aggregate corresponds to the first U-turn slot, and the second to the second U-turn slot.

For a particular f_{in} and the same travelled distance (say cars the turned on the second U-turn slot when $L_{unit} = 100$ versus cars that turned on the first U-turn slot when $L_{unit} = 200$), the distributions of $L_{unit} = 200$ have lower total time delays than those of $L_{unit} = 100$. The only case that $L_{unit} = 100$ has lower total time delay is when a car was able to make a turn with less travelled distance. This means that in terms of equal travel distance, a road system with fewer U-turn slots ($L_{unit} = 200$) will always be more lenient to turning cars. Otherwise, more U-turn slots means more cars turning earlier and they

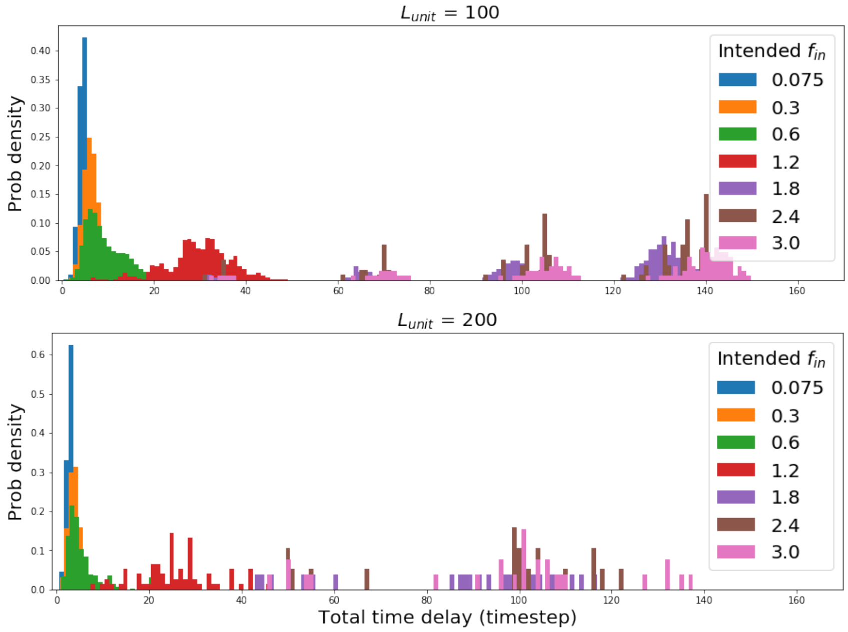

Figure 4: Total time delay distributions for the following L_{unit}: (a) 100 and (b) 200.

will be the only ones with less time spent on the road.

4 Conclusion

It was shown that it is possible to construct and analyze an N-chain system of paired U-turn slots based only on the properties of a single unit cell. This however requires the inflow and outflow rates to be equal and it was validated by the measured effective values. This also limits the analysis to cars that have the same origin and destination. Conditions for clogging to occur were identified for different values of the separation distance between opposing U-turn slots, where the more spaced they are the less susceptible it is to have a clogged state. It is also essential to avoid these states for the N-chain system to be constructed. Finally, while keeping the distance travelled the same before making a turn, a car on a road with fewer U-turn slots will always spend less time than one on a road with more slots. The latter must make a turn earlier (effectively cutting the distance travelled) if it wants to spend less time in the system.

This study lays out the effects on turning capacity for different traffic conditions and separation distance between U-turn slots and, within the limits of unclogged states, show how different distributions of turning cars among these slots affect the overall traffic. With these findings, we can provide indicative values for U-turn slot window hours. We will be working on identifying specific distributions that yield more total U-turn throughput or have less mean travel time. We can also extend our system to various vehicle types by changing cell occupancy in the road lattice and adding their corresponding behavioral rules.

Acknowledgments

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References

[1] J. S. Combinido and M. Lim, Modeling U-turn traffic flow, *Physica A* **389**, 3640 (2010).

[2] S. Dash, S. S. Mohapatra, and P. P. Dey, Estimation of critical gap of U-turns at uncontrolled median openings, *Transp. Lett.* **11**, 229 (2019).

[3] S. S. Mohapatra and P. P. Dey, Estimation of U-turn capacity at median openings, *J. Transp. Eng. A* **144**, 04018049 (2018).

[4] I. Fenis, D. Dailisan, and M. Lim, Interplay of behavior and traffic dynamics at u-turn slots, in *Proceedings of the 37th Samahang Pisika ng Pilipinas Physics Conference* (Tagbilaran City, Bohol, Philippines, 2019), SPP-2019-PB-22.