Interplay of behavior and traffic dynamics at U-turn slots

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Abstract

Driver behavior often complicates the modeling of U-turns slots. Using a modified Nagel-Schreckenberg model for paired U-turn slots, we simulate traffic at different conditions by varying the inflow rate p_{in} and outflow rate p_{out}, and for different probabilities p_u that a car that is entering the system will make a U-turn. We observe that congestion cascades from the inner lane to the adjacent lane due to the insistence in making a U-turn despite the presence of a long queue. We found transition points p_u^* on when this congestion occurs. The minimum obtained value is $p_u^* = 0.25 \pm 0.05$ which appears at high p_{in} and p_{out}. The results of our study can be a potential guide to designing U-turn slots while considering the traffic volume of vehicles that will make a U-turn.

Keywords: Traffic, U-turn, lane-changing

1 Introduction

In Metro Manila, U-turn slots are pervasive as an adaptive form of optimal signaling. In this work, we use the Nagel-Schreckenberg (NaSch) model [1] extended for U-turns by Combinido et al. [2]. The NaSch model is one of the simplest freeway traffic cellular automata simulators which imposes vehicle rules on a microscopic level. In contrast to a macroscopic model [3], it provides finer traffic dynamics and the ease of implementation of lane-changing.

Lane-changing [4–6] is commonly observed to be associated with a desire to maintain velocity when faced with slow moving vehicles ahead. In the context of U-turn traffic, the presence of U-turn slots on one side of the road incentivizes lane-changing. This promotes interaction as cars taking a U-turn move to the inner lane (assumed to be the U-turn lane) while non-turning cars simultaneously move to the remaining lanes.

A particular road configuration found in Metro Manila involves two opposing U-turn slots with separation distance L connecting two main roads. A car can essentially travel in a loop. One of its possible consequences is the occurrence of congestion when a high volume of cars intending to make a U-turn are involved, forming queues and potentially gridlocks on lanes used by these cars. It is important to identify the conditions when these happen to prevent undesired traffic states.

A key finding by Combinido et al. [2] on U-turn traffic is that free-flow is achieved only at low car inflow. However, aggregate measurements were taken on all lanes. Moreover, traffic was investigated after the U-turn.

In this paper, we use a modified NaSch model to investigate the effect on a paired U-turn slots when cars intending to make a U-turn and non-turning ones interact with the aim to move to desired lanes. We obtain separate results for each lane and show similarities and differences of dynamics across the lanes.

2 Methodology

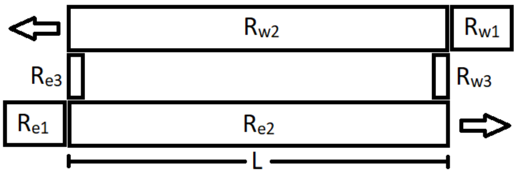


Figure 1: Road configuration. Arrows indicate direction of traffic and where the cars exit the system.

We implement the open boundary NaSch model, which removes the constraint of equal inflow and outflow rates. Our full system (Fig. 1) consists of eastbound and westbound roads connected by two opposing U-turn slots (R_{e3} and R_{w3}, 3 cells each). Each road has three lanes and is made up of a reservoir segment (R_{e1} and R_{w1}) with size 3 x 5 cells and a long segment (R_{e2} and R_{w2}) between the two U-turn slots with size 3 x L where $L = 100$ cells.

Cars enter the system at reservoir segments with a maximum inflow rate per lane p_{in} and exit at the ends of R_{e2} and R_{w2} with maximum outflow rate per lane p_{out}. A turning car (wants to make a U-turn) spawns with probability p_u, traversing the following route: R_{e1} (R_{w1}) $\rightarrow$ R_{e2} (R_{w2}) $\rightarrow$ R_{w3} (R_{e3}) $\rightarrow$ R_{w2} (R_{e2}). Otherwise, it is a non-turning car which heads straight to the exit with route: R_{e1} (R_{w1}) $\rightarrow$ R_{e2} (R_{w2}). Car states are updated in random sequential order. Each car occupies a single cell (cell length=5 m) [2] and updates every timestep $t \rightarrow t + 1$ (1.8 s) [2]. In a straight single lane, the i^{th} car moves according to the following NaSch rules:

R1 *Acceleration.* $v_i \rightarrow v_i + 1$ if $v_i < v_{max}$

R2 *Deceleration.* $v_i \rightarrow d_i$ if $v_i > d_i$ (d_i is the number of empty cells in front of the ith car)

R3 *Slowdown randomization.* $v_i \rightarrow v_i - 1$ with probability p

R4 *Forward movement.* Car moves v_i cells forward.

R1 allows cars to accelerate up to a maximum speed $v_{max} = 5$ cells/timestep. In the U-turn slots, the maximum speed is set to $v_{umax} = 1$ to account for safety while making a curve. R2 ensures no collisions between cars. The probability p in R3 accounts for fluctuations due to driving imperfections. It is set to $p = 0.065$ [2].

R5 *Lane changing.* To accomplish the desired routes of turning cars and non-turning cars, we apply a mixture of mandatory and discretionary [6] lane-changing rules: (a) a turning car (non-turning car) aims to go to the inner lane (middle or outer lanes); (b) changing to the adjacent lane is only allowed if the neighboring cell is unoccupied [4]; (c) the turning car is modeled to be indifferent to lane conventions such that it will stop at the last cell of either the inner or middle lane to make sure it can make a turn; (d) the non-turning car will aim to avoid the inner lane but, once in the middle or outer lane, will freely change between the two lanes to minimize deceleration [5]; and (e) a car, regardless of type, will always exit if it is in the outer lane at the end of the road.

Cars from the reservoir eventually interact with cars exiting the U-turn. Inertial considerations give cars from the reservoir a higher probability (0.7) [2] to be prioritized on update than the generally slower-moving cars from the U-turn.

The model was simulated for 4000 timesteps with the following rule sequence: 5-1-2-3-4. The following parameters are varied: p_u, p_{in}, and p_{out}. Both roads are given similar parameters during simulation. Measurements are done after 3000 timesteps to avoid transient effects. Taking advantage of symmetry, only lanes in R_{e2} are investigated. For each lane, the mean velocity $\bar{v}$ computed over the last 1000 timesteps is used to characterize the speed distribution.

3 Results and Discussion

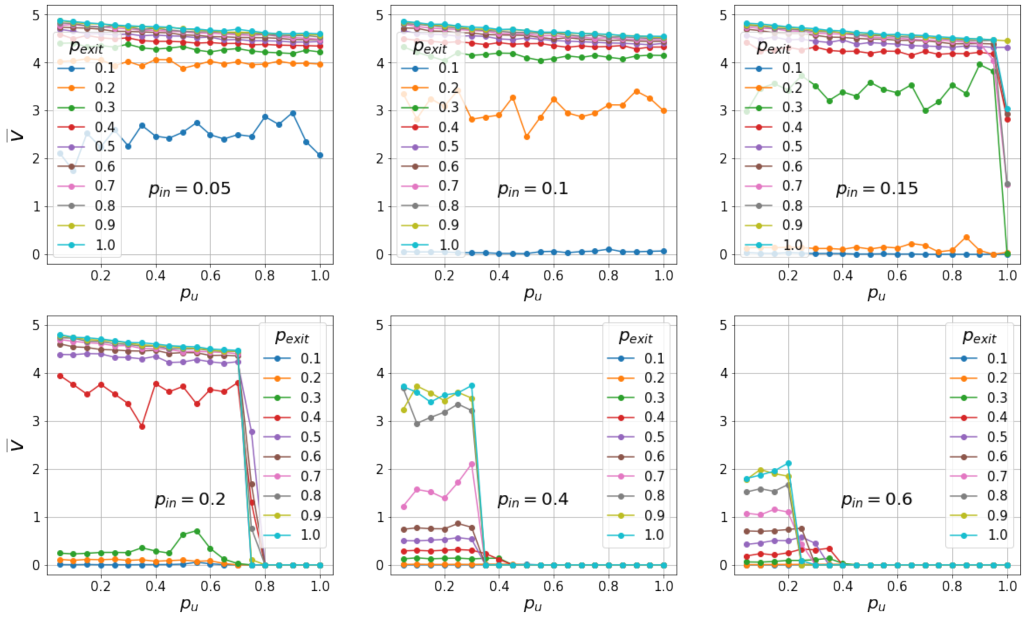
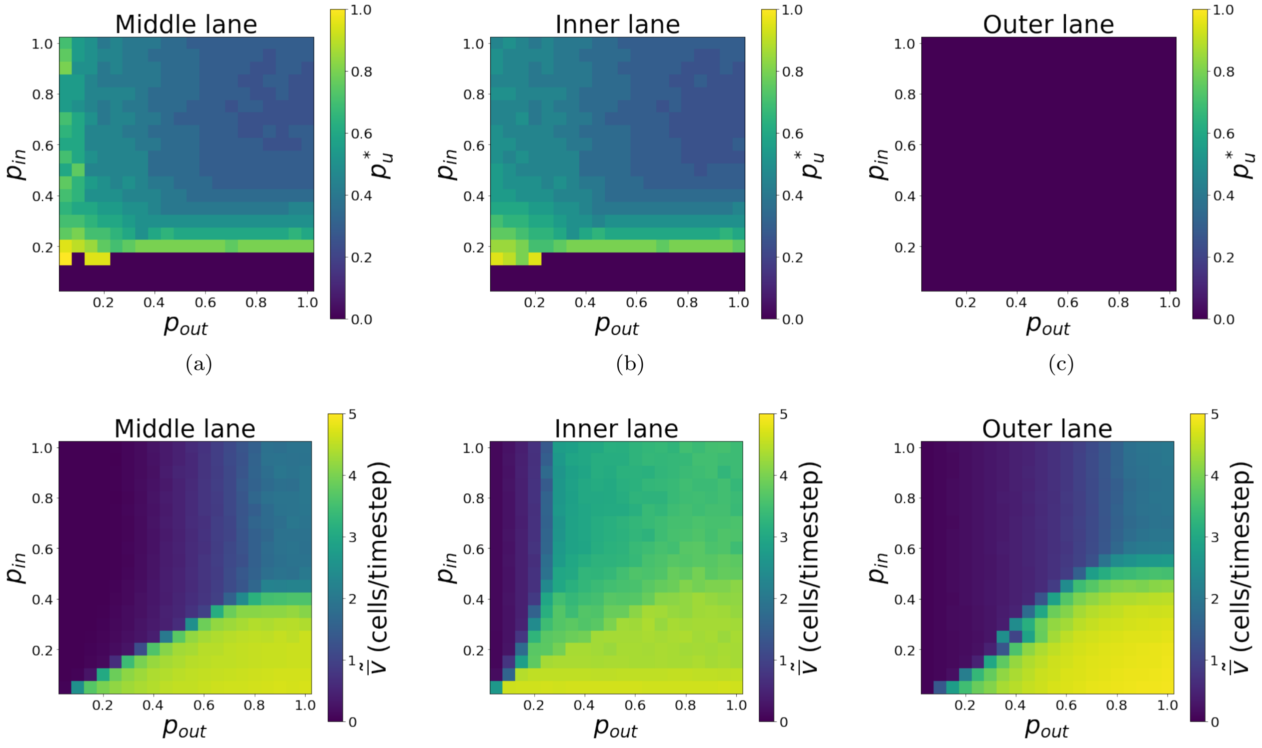


Figure 2: Middle lane: mean velocity profile at different values of U-turn probability p_u and inflow and outflow rates p_{in} and p_{out}.



(d) (e) (f)

Figure 3: (a-c) Transition point p_u^* and (d-f) median of the mean velocity $\tilde{\bar{v}}$ at different values of flow rates p_{in} and p_{out} for middle, inner, and outer lanes respectively. In (a-c), a value of zero means that no transition point was observed.

Figure 2 shows the mean velocity in the middle lane for different values of inflow rate, outflow rate, and U-turn probability. At low inflow rates ($p_{in} < 0.2$, Fig. 2), no transition was observed in the mean velocity along p_u. In this case, traffic in the middle lane is unaffected by the presence of turning cars. At higher inflow rates ($p_{in} \geq 0.2$, Fig. 2), transition points p_u^* appear where the mean velocity immediately drops to zero and the middle lane changes to a congested state. We plot p_u^* for different values of the boundary flow rates in Fig. 3a. At $p_{in} \geq 0.2$, the transition point generally decreases with increasing p_{in} and p_{out}. The minimum transition point obtained is $p_u^* = 0.25 \pm 0.05$ which occurs when both the inflow and outflow rates are near 1.0.

Figure 3d shows the median of the mean velocity $\tilde{\bar{v}}$ before crossing the transition point p_u^*. Free flow (lighter-colored region) occurs when $p_{in} < p_{out}$. Otherwise, cars are forced to interact with each other which decreases $\tilde{\bar{v}}$. As p_{in} is increased, a greater number of cars entering the middle lane results to more frequent interactions, requiring a larger outflow rate to achieve free flow. This case persists until $p_{in} \approx 0.4$, where the middle lane remains congested regardless of the outflow rate.

We calculate the emerging density averaged over time in the middle lane for different combinations of p_{in} and p_{out} using

$$\rho = \frac{1}{L(T - t_0)} \sum_{t=t_0}^{T} n_t \tag{1}$$

where n_t is the number of cars present in the middle lane at time t, $t_0 = 3000$, and $T = 4000$. We plot this against the mean velocity to obtain the fundamental diagram (Fig. 4). At low p_u, we get a wide range of density values. As we increase p_u, the plot becomes more sparse due to fewer realizable density values. Most of the points gather at $\rho = 1$, indicating that the middle lane becomes more vulnerable to congestion.

We find similar p_u^* plots (Fig. 3a and 3b) for the middle and inner lanes. This is expected since a congested inner lane forces a turning car in the middle lane to stop and stay at the last cell (Rule 5c) to ensure a U-turn, causing a buildup of congestion in the latter. In the outer lane no transition occurs all throughout (Fig. 3c) because a car can always exit in this lane (Rule 5e).

Cars in the inner lane travel at higher speeds for a wider range of traffic conditions (Fig. 3e). The

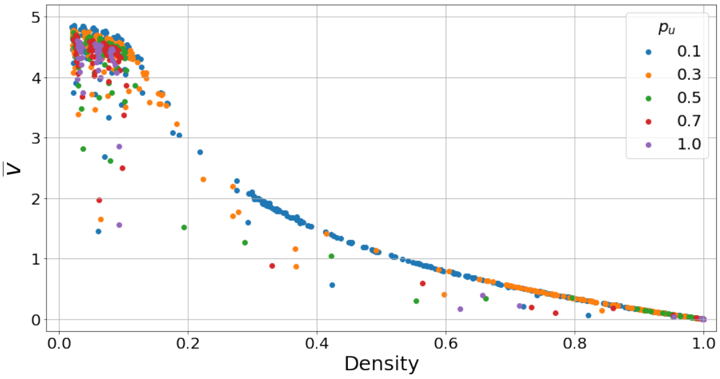


Figure 4: Fundamental diagram for middle lane at different values of p_u.

condition $p_{in} < p_{out}$ as a prerequisite for free flow loosely applies since turning cars avoid p_{out} by exiting at the U-turn slot. Instead, outflow rate at the opposite road influences traffic in this lane. The added region with higher speeds corresponds to lower values of p_u^* (see Fig. 3b). Thus, only a small number of turning cars are actually using the inner lane, minimizing interaction and deceleration. For the outer lane, we see a similar $\tilde{\bar{v}}$ plot as in the middle lane. It is unaffected by the presence of turning cars in the system.

In general, traffic in the middle lane behaves like in the outer lane below the transition point. Otherwise, congestion occurs and it develops into traffic in the inner lane.

4 Conclusion

We investigated the traffic dynamics of an open-boundary system with paired U-turn slots. All lanes exhibit two states: free-flow which occurs at low inflow rates, and congested otherwise. The addition of the U-turn probability parameter results to a difference in behavior between the inner and outer lanes. Congestion inevitably forms in the inner lane after reaching a particular value p_u^* of the U-turn probability. The lowest obtained value of this transition point ($p_u^* = 0.25 \pm 0.05$) occurs when both inflow and outflow rates are high. On the other hand, the outer lane is unaffected by the amount of turning cars present in the system. Traffic in the middle lane primarily depends on the state of the inner lane. Beyond the transition point, it also becomes congested. Otherwise, it exhibits similar dynamics as in the outer lane.

Paired U-turns are pervasive features of Metro Manila roads. While U-turn slot deployments were originally meant to be complex adaptive systems in the sense of having smart agents (i.e. drivers), our results indicate that a strong behavioral bias to continue on a set path (i.e. to make a U-turn) stymies the system and U-turns become ineffective since congestion and even jamming can easily develop. It remains to be investigated whether lengthening L between the two U-turn slots would be sufficient to address the issue.

Acknowledgments

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