CS166 Assignment 2 – Traffic Simulation

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In this report, stochastic cellular automata are used to simulate traffic on highways according to the model by Nagel & Schreckenberg (1992). Then, two lane highways are implemented in the vein of Rickert et al. (1996), and expanded to n-lane highways with torus topology. Flow and jams are analyzed using the models. Finally, the effect of driver behavior is studied through cut-off tendency during lane transfer.

Part 1: Traffic Jams on a Circular Road

Nagel & Schreckenberg (1992) presented a model for traffic simulation using simple arrays to represent lanes. In our implementation, an array value represents a tile of space in the road which a car could occupy, represented by an integer representing its speed: 0 for stationary cars, 1 for cars that can move 1 tile per timestep and so on. -1 is used to signify and empty tile. The boundaries are periodic, representing a looped road. Each instance of the model is instantiated with the following parameters:

1. *l_road*: the length of the road, in tiles.
2. *density*: the probability of any given tile to instantiate with a car occupying it. This stochastic initialization means that density values are only approximated during analysis.
3. *v_max*: the speed limit for any given car.
4. *p_slow*: the probability for any car to slow down randomly before moving.

The model's time evolution is carried out synchronously and stepwise, for a specified amount of simulation steps:

1. Acceleration: All cars speed up by 1, unless the speed limit has been reached.
2. Deceleration: All cars slow down to avoid collisions, exactly down to the amount of free space before the next car in the lane.
3. Randomized Deceleration: Each car slows down by 1 based on chance.
4. Movement: All cars move forward tiles equal to their speeds.

This model can be described as a class of stochastic cellular automata with v_max+2 states, a window of v_max+1 in front of each tile, and periodic boundaries. However, a pattern dictionary (rule-space) for this automaton would be very large, and so implementation was performed with array operations (python loops were considered but proved around 10 times more computationally expensive).[1]

Running the simulation for a certain set of parameters, we can examine the evolution of the state of the road with time by printing the state before each movement step:

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.............4........01.2..0...1.......5.....4...........3....3....3...4........2...2...2....3.....
.................4....1.2..01....2...........3....4..........4....4....3....4......2...2...3.....3..
3...................1.2..01.2.....3............4.....5..........3....3...4.....3....2...2....3.....
...3.................2..00.2..3......4............4......5........3....4....4....3...2...3.....3..
3.....4................001...2...4.......5............4.......4......3.....3....2...1..3....3.....
...4......4.............01.1....2.....4........5............5.......4.....3.....3...2..1....3....3..
3......5......4.........0.0.1.....2.......5.........5............4......4....3.....2..0.1......3....
...4........5.....4.....1.1..1......2..........4.........5...........5......2...3....01..1........3.
.4.....5.........3....1..1.1..2.......2............5..........5...........3...2....1.1.2..2.........
.....5......5.......1..1..0.1...2.......2...............4..........4.........1..3...1.2..1..3.......
..........4......3...1..0.0..2....2.......3.................4..........5......1....0.2..1.2....3....
..............4.....1.0.0.1....3....2........4..................5...........2..1...0...0.2..3.....4.
..5...............1..00.1..2......2...3..........4..................5........0.2..0...0...2...4....
.......5...........0.00..2...3......3....4...........4....................2...1...00...1.....2.....5
....4.......4......1.01....3....4......3.....5...........4...................2..1..01....2......3....
........5.......2...00.1......3.....4.....4.......5..........5.................1.0.1.2.....2.......4.
..4..........3....1.00..1........4......4.....5........5..........5............00..1..2.....2.......
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Figure 1. Evolution of a single lane over time. Parameters: l_road = 100, density=0.18, v_max=5, p_slow=0.5.

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[1] #optimization: Translated the entire 1-lane model to array operations in order to optimize execution.

We observe traffic jams, resulting from randomized deceleration of certain cars forcing others to stop. Since cars do not slow down to keep distance in the model, and do not consider their neighbors' speeds to accelerate in unison, driver response delay is simulated, generating jams that advance backwards through the road as long as cars keep flowing in.

We keep track of flow by averaging the number of cars passing through a certain tile over the simulation time, and run 100 simulations at 35 different density settings. By plotting we observe the effect of density on flow:

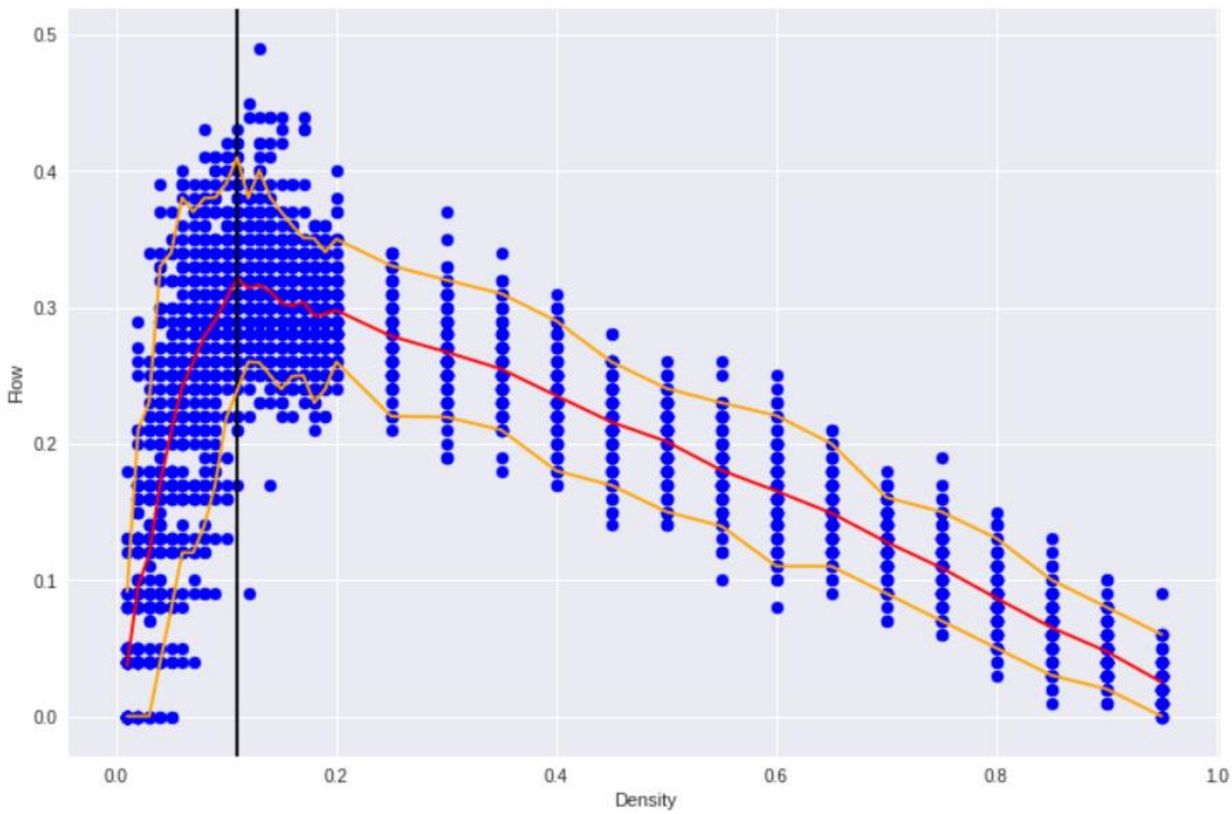

Figure 2. Average flow over density for 100 simulations of 100 steps at 35 different values of density with the same parameters as figure 1. In red: the average flow over all simulations. In orange: the 5% and 95% percentile flow value to visualize the confidence interval. In black: peak average flow.

We observe a clear peak average flow around density 0.11. Beforehand, less cars make use of the space, and afterwards jams slow the traffic along the road. According to Nagel & Schreckenberg (1992), this behavior approximates real-life distributions. We observe a peak flow of 0.321 with a standard deviation of 0.053 at the peak.

Part 2: Multilane Highways

Rickert at al. (1996) proposed an extension to the model to simulate two lane highways. It inserts a lane switch step before the other update steps. Each car which has a speed higher than the free space ahead of it considers swapping lanes, and only does so if the coast is clear ahead on that lane according to its current speed, and if the other lane is also clear for a length equal to v_max behind it. A new parameter, *p*_switch, determines the probability of each car switching lanes, and then the car switches lane and the other steps execute as before.

```
..4.......2...2.......................5...........5..........4...........3....2..000000.0000........
.2...........5.............5.....4............4...........5....................0.00...0.0.0.1..2....

......4.....2...3...............5..........5...........4.........5..........3...0000001.0000........
...3..............5..................5............4............4...............1.01...1.1.0..1...2..

..........3...2....3.................4..........4..........4..........5........0000000.00000........
......4................5..................5...........5............4............00.1...1.01...2....2

.............1..3.....3..................4..........4..........5...........3...0000001.00000........
.3........5.................5..................4...........5...........5........00..1...00.1....2...

..............1....3.....3...................4..........4...........5.........0000000.000000........
....4..........5.................4.................5............5...........2...01...2..01..1.....3.

...............2......4.....3....................4..........4............4....0000000.000001........
.4......4...........5................4..................4............5........0.1.2....00.1..2......

.................3........3....3.....................5..........5............00000000.00001.1.......
.....5......4............4...............4..................4.............2...0..2..1..01..1...3....

....................4........4....3.......................4..........4.......00000001.0000.1.1......
..........5.....5............5...............5..................5...........0.1....1.0.1.2..1.....4.
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Figure 3. Evolution of a two lane model over time with the same parameters as in figure 1. Backpropagating jams still occur, but some cars are able to dodge them by changing lanes.

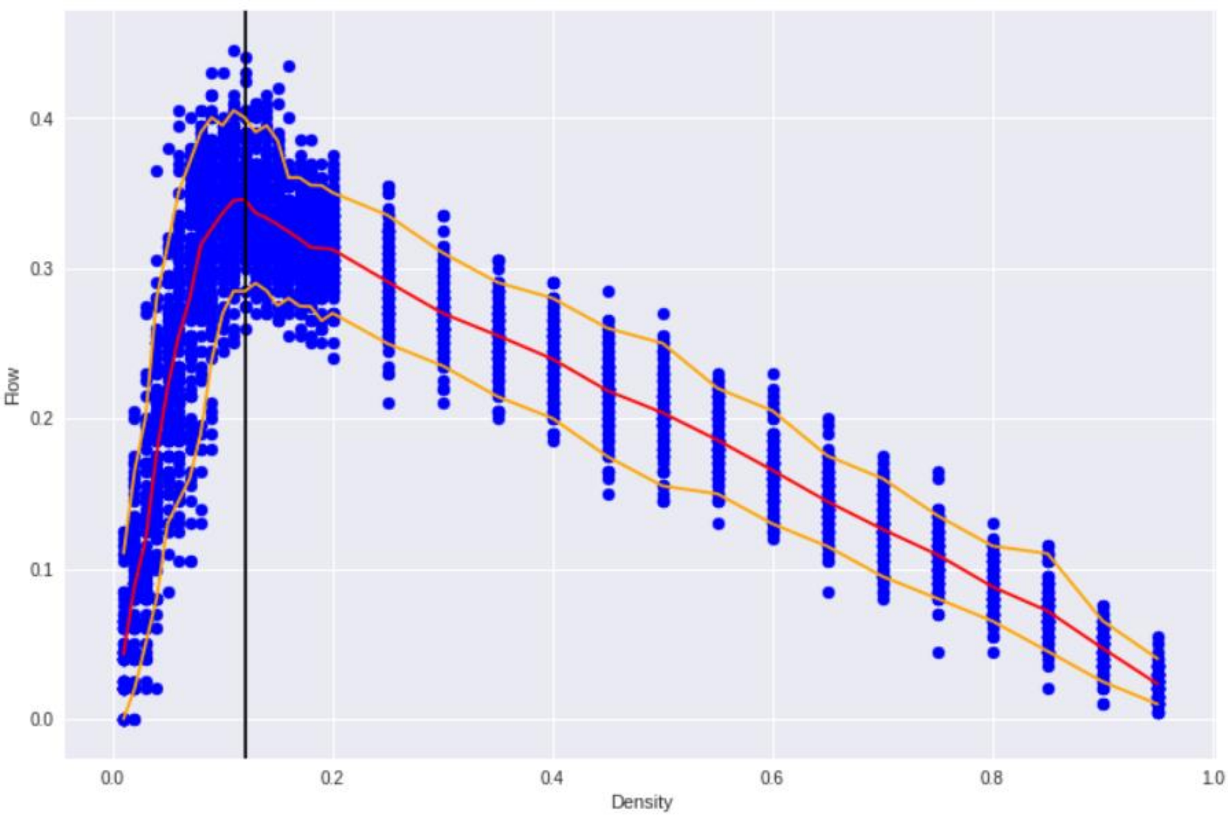

Figure 4. Average flow over density for a 2-lane model, with 100 simulations of 100 steps at 35 different values of density and the same parameters as figure 1.

With high densities, these conditions for a clear other lane don't allow for many lane switches to occur, and with low densities the desire for lane changes is rarer, but we do observe an increase in peak flow by ~%7 to 0.346. Maintaining the same density for two lanes calls for twice the number of cars, which tightens our standard deviation to 0.035.[2]

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[2] #significance: Implemented percentile visualizations and analyzed changes in standard deviation

But how does the model generalize to more lanes? We've implemented an n-lane model where lane switching is limited to one direction, with periodic lane boundaries (a topological torus). Examining their flow behavior, we see again a tightening of standard deviations coupled with small increases of peak flow, to 0.355, 0.361 and 0.362 for 3, 4 and 5 lanes, increases of 2.6%, 1.6% and 0.3% respectively. It seems that extra lanes exhibit diminishing returns, since car number rises proportionally and cars care only allowed to move one lane each time step.

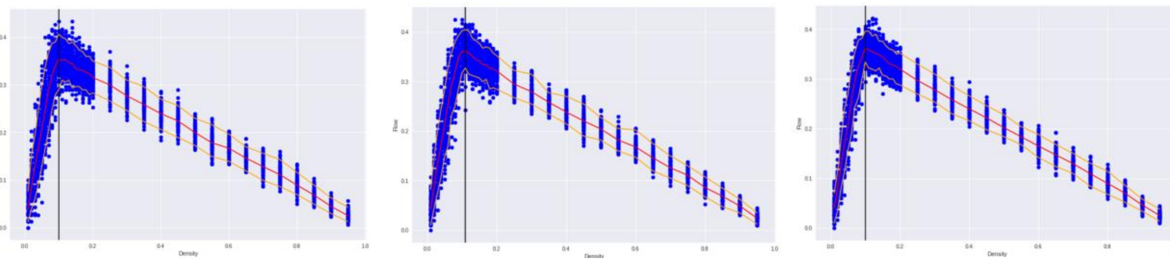

Figure 5. Flow over density for 3,4 and 5 lane models, with similar simulation and model parameters as figures 2 and 4.

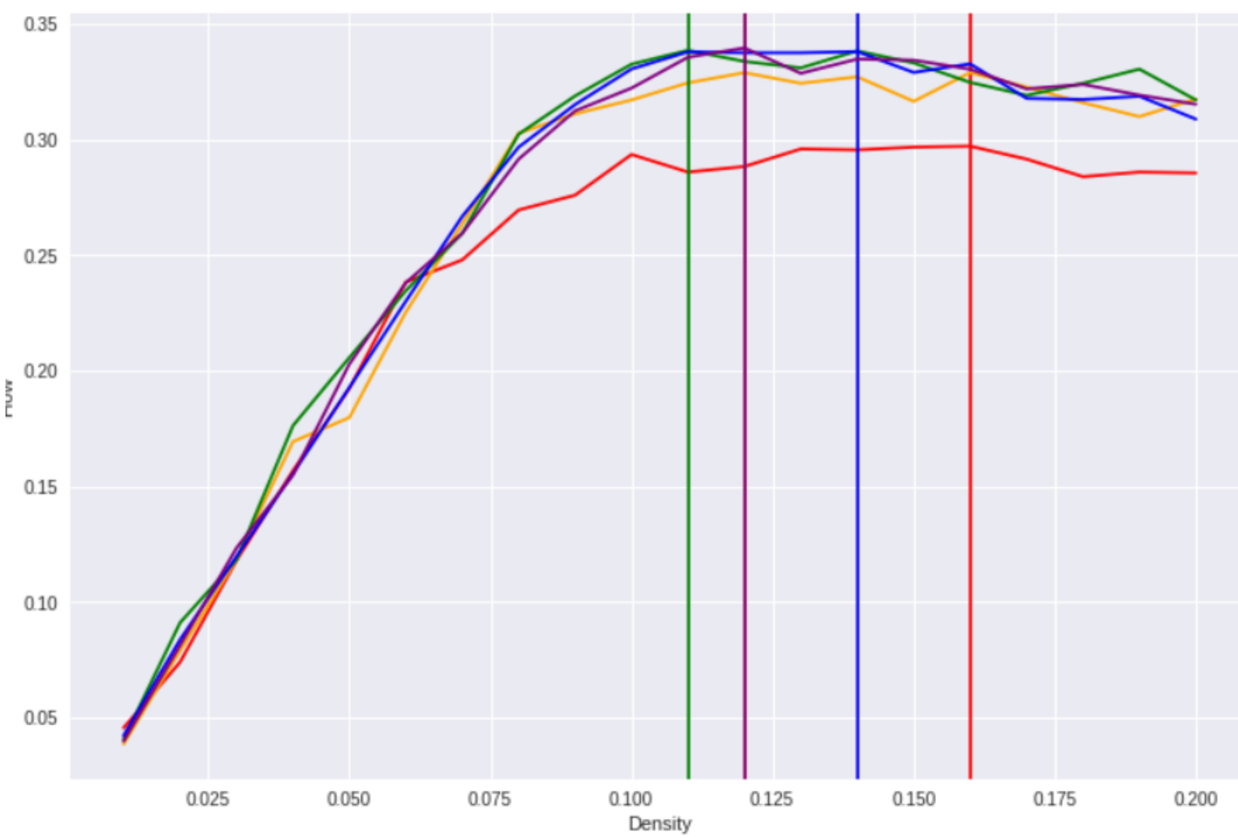

Figure 6. Closeup on peaks of 2,3,4 and 5 lane models (red, orange, green, blue, purple respectively), exhibiting an increase in peak height with diminishing returns. The peak density doesn't coherently co-vary with n_lanes.

Part 3: Bad Driver Behavior

Finally, we examine the effect of driver behavior on flow. Bad driver behavior can be modelled as increases probability to slow down, or as a deviation from some safe-distance-keeping rule one might implement. For this report the distance drivers look back to make sure the coast is clear before changing lanes was examined. Decreasing this distance makes drivers likely to recklessly cut off other drivers and leave traffic jams in their wake, for their own selfish benefit. We observe a decrease in peak flow from 0.364 to 0.345 between lookback 5 and 0.

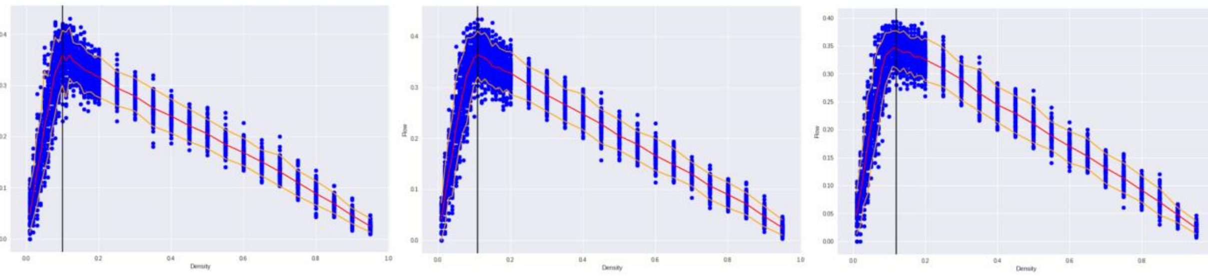

Figure 7. Flow over density for 3 lane models with lookback 5,2 and 0, with similar simulation and model parameters as figures 2,4 and 5.

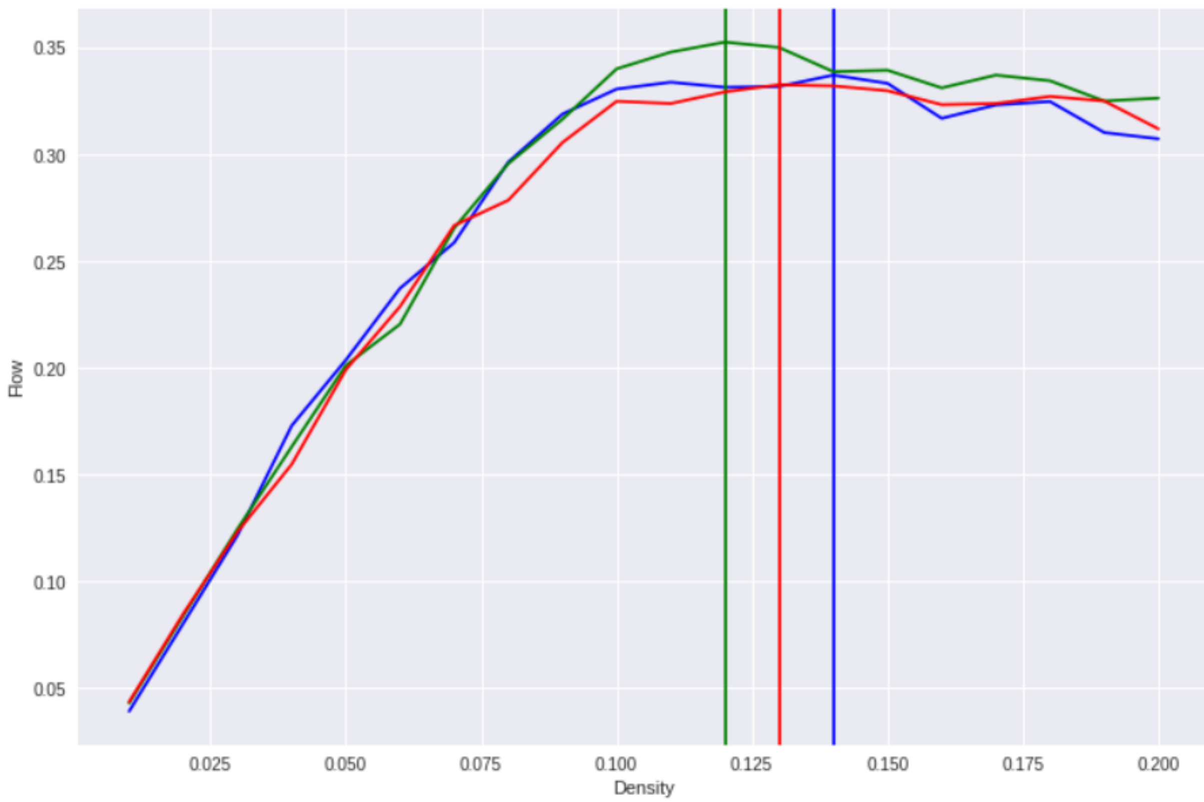

Figure 8. Close-up of peak densities with lookback 0,2 and 5 (red, green, blue respectively).

Applicability to Argentina and Future Work

Argentinian highways comprise 0.3% of roads in the country. This value is drastically lower than in other western countries where the empirical data of the original research was collected (Canada, United States), where highways comprise around 1.6% of roads. However, similar traffic rules apply on highways in Argentina, with similar speed limits (120-130 km/h). Interestingly, Buenos Aires City limits highway traffic to 100 km/h, which might impact the maximum flow value, but not on the dependence of flow on density. The main limitations of the model are general and apply to the Argentinian context as well as others, which would be helpful to expand on in future iterations.

In-lane driver behavior: A behavior that's been shown to have great impact on the emergence of congestion is distance keeping. Since jams are produced due to driver delay to sudden changes in the neighbor's speeds, maximizing response-time is an effective tool to grant robustness to the system. Modeling a tendency to keep distance should greatly improve flow rate. Additionally, a dependence of the randomized probability for deceleration on speed might add a dimension to the exploration of reaction time affecting driver behavior.

Lane-switching behavior: Since the n-lane implementation was an extension of the 2-lane model, an artifact remained allowing only switches to one direction, with periodic boundaries. Implementing the ability to switch lanes two ways might increase the overall flow improvement, but I hypothesize that the same diminishing returns schema will be seen in that case as well, since cars are still limited to move only one lane at a time. A more realistic model will break the symmetrical lane-switching behavior and take into account laws designating the left lanes for passing only, prompting cars to return right when possible.

Highway Features: Other sources of unexpected decelerations often come from lane merges, speed cameras, traffic lights and intersections. Off- and on-ramps also introduce a dimension of realism with unexpected obstacles entering the system, and drivers reaching their destination requiring them to forcefully change lanes.

References

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