Title

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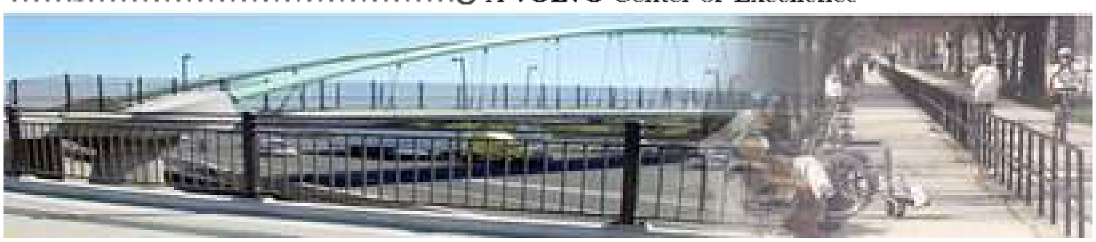

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Abstract

A simple symmetric network consisting of two tangent rings on which vehicles obey the Kinematic Wave Theory of traffic flow and can switch rings at the point of tangency is studied. An on-line adaptive simulation reveals that if there is any turning whatsoever the two-ring system becomes unevenly loaded for densities greater than the optimal density. This reduces flow. Furthermore, the two-ring system jams at significantly lower densities than the maximum density possible.

1 Introduction

It has been proposed in Daganzo (2005) that a well-defined, robust, and reproducible relationship between the average flow and average density on a traffic network (known as the 'Macroscopic Fundamental Diagram' or MFD) arises if the network is uniformly loaded so that all links are similarly congested. Daganzo and Geroliminis (2008) furthered this by showing that an MFD arises in traffic networks consisting of a single-route if vehicles obey the Kinematic Wave Theory of traffic flow (Lighthill and Whitham, 1955; Richards, 1956). This reference also gives explicit formulae to calculate the MFD as a function of the length of individual links, their individual fundamental diagrams and the intersection control schemes. Daganzo and Geroliminis (2008) also proposed that these formulae should apply to a multi-route network if the routes are similar and the number of vehicles using each route are the same and constant over time. These conditions should be expected to occur on a homogeneous, redundant network (such as a symmetric grid network) with slow-changing demand; after all, network redundancy allows drivers to choose between the different routes adaptively and, therefore, the densities of each of the routes should be similar.

However, when Geroliminis and Daganzo (2008) studied real networks that approximately meet these conditions (San Francisco, California and Yokohama, Japan) it was found that the formulae over-predict the observed flow-density relationship in the congested regime. This was also confirmed by Gonzales et al. (2009) which created the MFD of Nairobi, Kenya and compared it to the previous two networks. The latter reference also noted that while the observed flow-density relationship for all three networks are consistent for low network densities, there is considerable scatter in the congested branch of the MFDs that were created using simulated data (San Francisco and Nairobi). These phenomena were also noted in Mazloumian et al. (2009) which attributed the cause to stochastic variations in link densities due to vehicular granularity. However, this does not explain the low densities at which the networks jam. It has been recently proposed that the main cause of the scatter, the low flows, and the network's propensity to jam at low densities is an instability created by turning maneuvers such that uniformly loaded links are not sustainable (Daganzo et al., 2010).

This paper empirically demonstrates these phenomena with a simple system that isolates the effects of turns. Section 2 describes the simple system; Section 3 describes the interactive cellular automata simulation that was created to study the effects in question; Section 4 presents the observed phenomena; and Section 5 summarizes the conclusions.

2 Two-Ring System

Here the simplest system that contains multiple overlapping routes and turning between these routes is considered. This system consists of two tangentially connected rings that only interact at the tangent point (also called the turning point); see Figure 1. To reduce complexity and further isolate the effects of route choice and turning, it is assumed that both rings are perfectly symmetric. That is, they each have the same length, L, and the same fundamental diagram as shown in Figure 2.

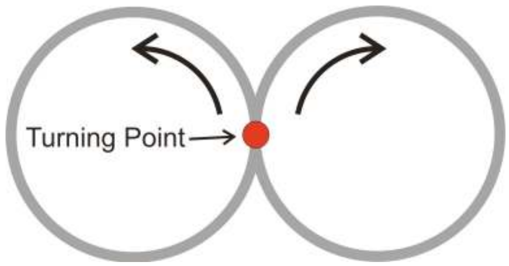


Figure 1. Simplest system that isolates the effect of turns.

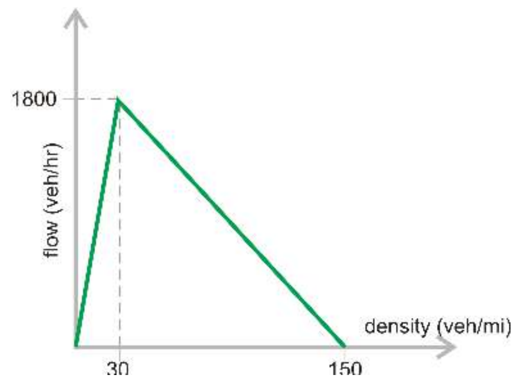


Figure 2. Fundamental diagram of individual rings.

Vehicles travel counter-clockwise on the left-hand ring and clockwise on the right-hand ring and can only maneuver between the two rings at the turning point. In this system, vehicles do not have destinations; they simply travel indefinitely in the system using the two rings available to them. It is assumed that vehicles do not have a preference for either ring and that each vehicle has the same fixed probability, P_T, of turning from one ring to the other upon arriving at the turning point. Using a fixed turning probability is analogous to vehicles traveling through the network with predetermined routing decisions that are independent of traffic conditions in the system.

A conflict exists at the turning point when two vehicles arrive simultaneously and wish to travel to the same downstream location. This will occur whenever one vehicle wishes to change rings while the other wishes to remain on its current ring. It is assumed here that both turning and through-moving vehicles have equal priority. Therefore, when this conflict occurs one vehicle is randomly assigned priority to move while the other vehicle must yield.

3 Interactive Simulation

An interactive simulation was created in order to study the two-ring system proposed in Section 2. The simulation is available on-line at `http://www.ce.berkeley.edu/~daganzo/home.html`. The details and logic of the simulation are presented in Section 3.1 and the simulation interface is described in Section 3.2.

3.1 Simulation Logic

The simulation was coded in the JAVA programming language using the CA(M) cellular automata model proposed in Daganzo (2006) because it is simple to code. As explained in Daganzo (2006), the CA(M) model is equivalent both to the Kinematic Wave Theory of traffic flow and to the CA(L) model in Nagel and Schreckenberg (1992). The model is a discrete simulation in which the ring is broken up into homogeneous cells, each the length of an individual jam spacing ($\Delta x = 1/150$ mi = 35.2 ft). The vehicle locations are updated every $\Delta t = 0.4$ sec as required by the CA(M) method ($\Delta x/\Delta t$ is the free flow speed). Each ring was given an arbitrary length of $L = 0.4$ mi which is equivalent to the space required by 60 vehicles at jam density.

The number of vehicles in the system at any point in time is interactively specified by the user. Only even numbers are allowed to ensure that it is always possible for each ring to contain the same number of vehicles. Vehicles are added or taken away the system at the turning point. At the start of the simulation, vehicles are loaded evenly between the two rings. If the user increases the number of vehicles while the simulation is running, new vehicles will be loaded onto whichever ring has a gap available for them to enter at the turning point. Vehicles only leave the system if the user decreases the number of vehicles in the system. If this is done, vehicles will exit the system as they arrive just upstream of the turning point until the actual number of vehicles in the system is equal to the number specified by the user.

The simulation can include traffic signals. To ensure a completely symmetric network, signals on both rings share the same signal settings except the signals on the left-hand ring are offset by one-half of the signal cycle with those of the right-hand ring. If included, signals are evenly spaced along each ring with the first signal placed at the turning point. The presence of a signal at the turning point eliminates the merging conflict there.

3.2 Simulation Interface

A snapshot of the simulation interface is shown in Figure 3. The panel on the left-hand side is used to alter the simulation settings. The user can change the turning probability (P_T), the total number of vehicles in the system, the number of signals present on each ring, the simulation speed, and the cycle length, green time, and offset of the signals. The two leftmost buttons on the bottom of the input panel start (or pause) and reset the simulation, respectively. The second two buttons (labeled 'L-to-R' and 'R-to-L') force vehicles to turn from the left to right-hand ring and right to left-hand ring, respectively. These buttons only work for one vehicle at a time but can be pressed repeatedly. Each click acts on the next vehicle to arrive at the turning point from the relevant ring. The reason for including these buttons will be described in Section 4.2.

The location of the vehicles on each of the two rings is represented by the circles in the top-right of Figure 3. Signals are represented by colored lines that extend across the path of the vehicles. The color of the line represents the signal phase: a red line represents the red phase which prevents vehicle movement while a green line represents the green phase which allows vehicles to pass through freely.

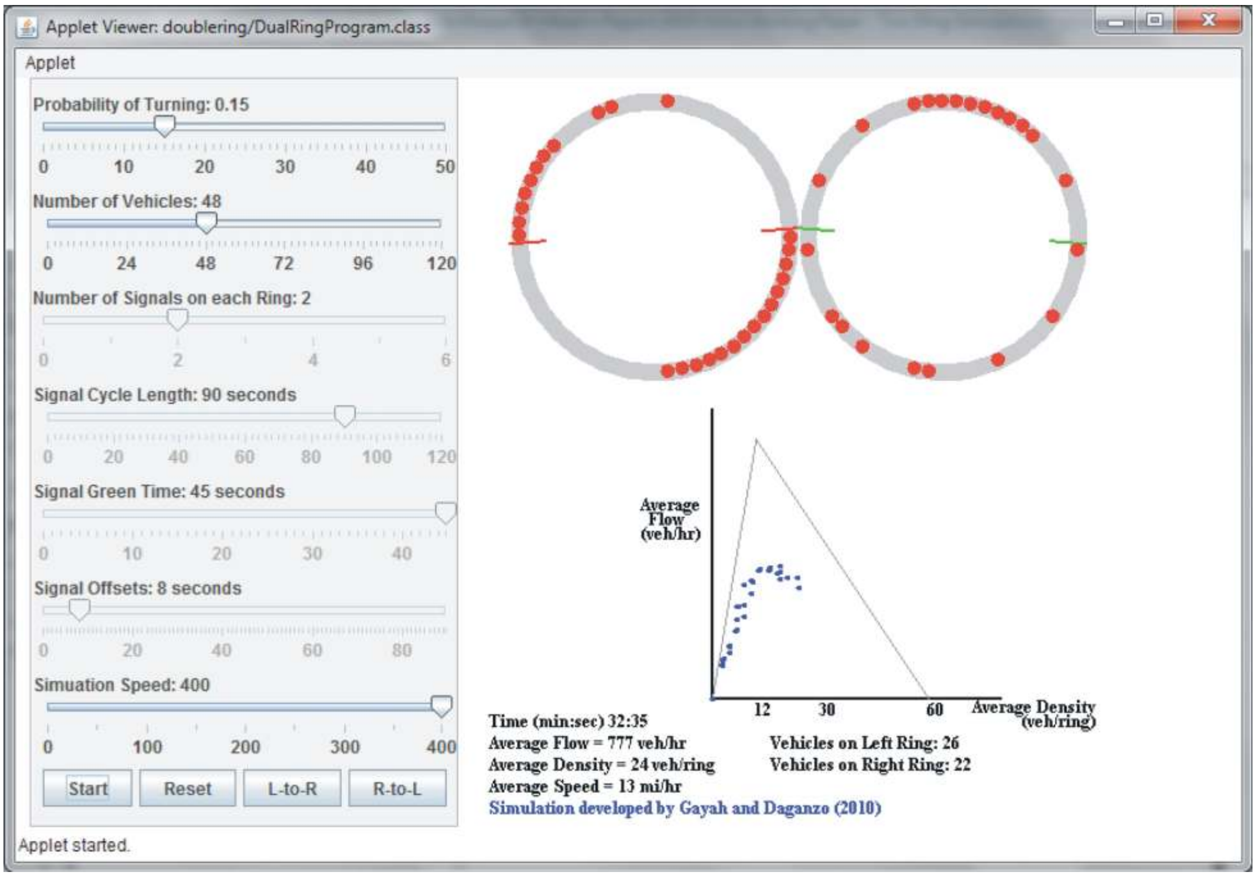


Figure 3. Snapshot of simulation showing user inputs, two-ring system, and flow-density relationship.

While the simulation runs, averages of the flow and density in the system are calculated at discrete one-minute intervals using Edie's generalized definitions (Edie, 1965). In the bottom-right of the simulation display, these flow-density pairs are plotted for the last 100 one-minute intervals. The fundamental diagram of the individual rings is also plotted on this plane as a gray curve for visual comparison. The text at the bottom-right of simulation displays the average flow, density and speed of vehicles in the system as the simulation runs, as well as the number of vehicles on each ring at any point in time.

4 Phenomena to Observe

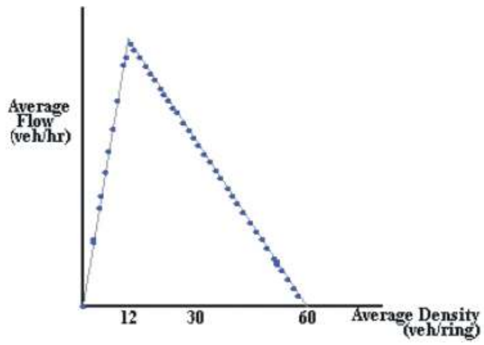
This section describes some of the phenomena that can be observed. Section 4.1 describes the behavior of the system when individual vehicles use only a single ring to travel in the system ($P_T = 0$), and Section 4.2 the behavior when individual vehicles are allowed to turn and use multiple routes ($P_T > 0$).

4.1 Vehicles use a Single Route

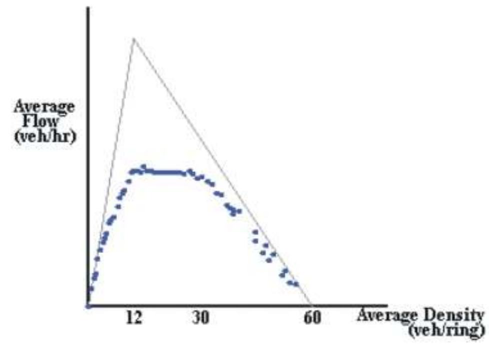
When the probability of turning, P_T, is equal to zero, vehicles cannot change rings as they move through the system; instead, each vehicle stays on the ring that it starts on. In this case, the two rings do not interact and can be treated independently. Therefore, since the rings start out evenly loaded, they stay evenly loaded. As a result, the system should behave as described in Daganzo and Geroliminis (2008); i.e., the observed flow-density pairs should be closely grouped along the theoretical MFD of the ring.

For example, when no signals are present, the MFD of a single ring (and thus the flow-density relationship of the entire system) is equal to the fundamental diagram of the ring. The reader can confirm that this occurs with the on-line simulation. Try the following: 1) set the Probability of Turning, Number of Signals on each Ring, and Number of Vehicles to 0; 2) start the simulation; 3) slowly increase the number of vehicles in the system until the system becomes completely jammed (this can be done by clicking the right-hand side of the Number of Vehicles slider once every 2-3 minutes of simulation time). The flow-density pattern will be almost exactly equal to the fundamental diagram; see an example of one such run in Figure 4(a). This is true even if vehicles are added to the system fairly rapidly.

Even with the presence of traffic signals,the observed flow-density pattern follows the theoretical formulae. Figure 4(b) shows the flow-density pattern when a single signal is present on each ring with a cycle length of 60 seconds and a green time of 30 seconds. This pattern was created by loading the vehicles gradually but rapidly; i.e., adding a pair of vehicles to the system every 2-3 minutes of simulation time. The reader can confirm that the observed flow-density pattern is that predicted by the 'cuts' in Daganzo and Geroliminis (2008). Note that there is some scatter in the observed flow-density relationship due to the use of discrete one-minute intervals to calculate the average flow and density, but this scatter is minimal.



(a)



(b)

Figure 4. Flow-Density relationship when $P_T = 0$ and (a) No signals are present; (b) One signal is present ($C = 60$ sec; $G = 30$ sec).

4.2 Vehicles Use Multiple Routes

When the probability of turning, P_T, is greater than 0, vehicles are able to use both of the rings as they travel through the system, the exact route varying for individual vehicles. Using the simulation, the reader can see that the flow-density pattern now changes considerably from the relationship that exists when vehicles used only a single route. Try the following: 1) set the Probability of Turning to 0.15, Number of Signals on each Ring and Number of Vehicles to 0; 2) start the simulation; 3) gradually increase the number of vehicles in the system until the system becomes completely jammed. Do this for different loading rates and observe that if loading is not too rapid the flow-density pattern will resemble Figure 5.

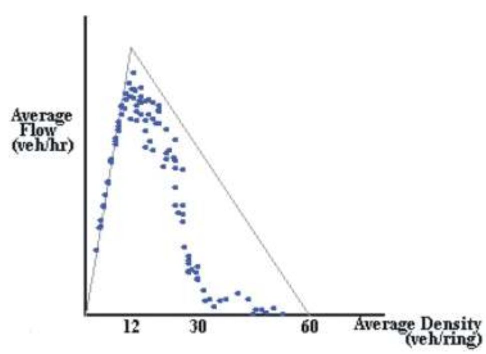


Figure 5. Flow-Density relationship when $P_T = 0.15$ and no signals are present.

Figure 5 displays several phenomena that are caused by the existence of turning maneuvers. At lower densities (between 1 and 6 vehicles per ring), the observed flow-density points consistently fall on the fundamental diagram (as expected from theory). This occurs because the system spends most of the time with both rings nearly equally loaded, always operating in free flow conditions. At slightly higher densities (between 7 and 12 vehicles per ring), the system continues to spend most of the time with both rings nearly equally loaded but every once in a while one rings spills over into the congested regime. This causes the flow-density points to be scattered and lie slightly below the gray triangle. This effect is due to the granularity of the simulation and diminishes for larger rings that can contain many vehicles. Flow is also reduced by conflicts at the point of tangency, which delay vehicles and impede their progress.

At higher densities (greater than 13 vehicles per ring), however, the system no longer spends most of the time with both rings nearly equally loaded-now, the system spends most of the time with one ring in congestion and the other in the free flow range. The rings tend to stay in this asymmetric pattern for extended periods of time but once in a while the ring densities flip and settle into the opposite pattern. This imbalance occurs systematically as the reader can verify by repeating the simulation. For example, try the following: 1) set the Probability of Turning to 0.05, Number of Signals on each Ring to 0 and Number of Vehicles to 40; 2) start the simulation. The system will start evenly loaded with 20 vehicles on each ring. However, as the simulation runs, the average flow changes with the numbers of vehicles on each ring. In the beginning, when each ring contains about the same number of vehicles the flow is high (about 1500 veh/hr). But, as the rings become unevenly loaded the flow reduces. For this particular example, the rings stabilize with one containing about 33 vehicles and the other only 7. This imbalance causes the observed average flow (about 1000 veh/hr) to be much less than the theoretical average flow if both rings were evenly loaded (1500 veh/hr). For this particular example, it is very rare that the congestion will flip between the rings. To observe flipping, retry the example with fewer vehicles and/or a larger turning probability; e.g. increase the Probability of Turning to 0.5.

The simulation also unveils another interesting phenomenon—the system now tends to gridlock (completely jam with no flow) for densities much less than the jam density of the system. In Figure 5, the system seems to become jammed (has zero flow with a positive density) at a density of about two-thirds of the jam density. In fact, the two-ring system will tend to jam for any density greater than or equal to one-half of the jam density. The reader can again confirm this with the simulation. Try the following: 1) set the Probability of Turning to any value between 0 and 0.5, Number of Signals on each Ring to 0, and Number of Vehicles to 60 (30 vehicles per ring or one-half of the jam density); 2) start the simulation. The two rings will initially be loaded evenly (with 30 vehicles on each ring). As time elapses, the rings will eventually become unbalanced with one more congested than the other. In time, the more congested ring will continue to become more and more congested. Eventually, this ring will become completely jammed while the other ring will be completely empty. Due to the stochastic nature of the simulation, this may take some time, but the system always tends to this jammed state.

When the system has an average density greater than one-half of the jam density, one of rings will become completely congested, as before. However, the less congested ring will also jam because one of the vehicles on it will try to turn onto the completely jammed ring. This vehicle will block the path of the vehicles behind it, reducing the flow on this ring to zero as well. An example of this is shown in Figure 6. Once this happens, the user can use the 'L-to-R' and 'R-to-L' buttons at the bottom of the input panel to 'un-jam' the system by forcing vehicles out of the full ring, but when the clicks are stopped the system invariably returns to the jammed state.

The phenomena described in this subsection are independent of the value of P_T. As long as

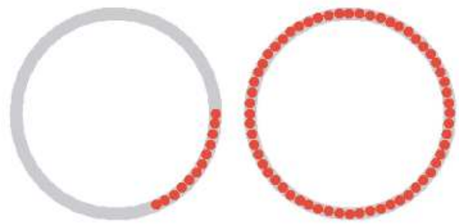


Figure 6. Potential jamming pattern of the two-ring system.

$P_T > 0$ and route choice is present, they will occur. The choice of P_T changes only the amount of scatter and the average time required for the system to jam if there are a sufficient number of vehicles. When P_T is very low, vehicles change between the two rings less frequently and a ring is more likely to stay congested once it becomes congested. When P_T is near 0.5, vehicles switch more frequently and the congestion may flip back and forth between the two rings multiple times before one eventually becomes completely jammed.

The phenomena described in this section also occur with the presence of traffic signals on the rings[1]. Try the following: 1) set the Probability of Turning to any value between 0 and 0.5, Number of Signals on each Ring to 2, Cycle Length to 90, Green Time to 45, Offset to 13 and Number of Vehicles to 60 (again, 30 vehicles per ring or one-half of the jam density); 2) start the simulation. The rings will become unevenly loaded until one eventually jams.

5 Conclusion

Simulations show that the availability of multiple routes and the opportunity to turn create an instability in a simple (two-ring) traffic network. At low network densities, when both rings operate in free flow, the rings are evenly balanced and the flow-density relationship is the same as that predicted in Daganzo and Geroliminis (2008). At higher densities, when the system is congested, the rings become unevenly loaded and the actual flow-density pattern becomes more scattered and considerably below the theoretical prediction. This unbalancedness occurs systematically. It also causes the network to jam at densities much lower than the jam density of the system. This is a phenomenon that has been observed before in Geroliminis and Daganzo (2008) and Gonzales et al. (2009).

This simulation assumes that drivers turn independent of traffic congestion, as if they used a predetermined routing strategy. However, (some) real drivers make (some) routing decisions in real-time, deviating from their preferred path if it is too congested. Therefore, while this work does

[1] Certain combinations of cycle lengths, green times, and signal offsets cause the forward- and backward-moving waves to become synchronized, and this reduces the magnitude of the phenomena. Here is one example: four signals on each ring with a cycle length of 120 seconds, green time of 30 seconds and an offset of 0 seconds. Note how the rings still settle with uneven accumulations and reduced flows, but do not completely jam. Note too how this synchronization results in turning vehicles in one ring becoming 'blocked' by queues in the other. This blockage facilitates the transfer of vehicles from the more congested ring to the less congested ring, partly offsetting the destabilizing forces that push vehicles onto the more congested ring.

show that an instability arises in traffic networks when multiple routes are present, further work is needed to examine the effect of adaptive routing.

Acknowledgments

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