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Analysis of Capacity Drop at Congestion toward Better Environment

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Introduction

Transportation is one of the main man-made sources of polluting emissions, which account for about 45% of nationwide emissions. Highway vehicles contribute nearly 75% of the total transportation-related emissions [1]. Moreover, emissions during idling operations in congested roadways are higher. Emission levels depend also on the change in speed and acceleration of vehicles within a traffic stream. These emissions have adverse effects on the environment and subsequently on the overall human health. Accordingly, it is important to look for solutions to protect the environment by preventing or reducing the factors that cause bad environmental effects. This essay attempts to present and analyze the factors related to congestion causing these increased emissions by analyzing causes for capacity drop at the onset of congestion. Such capacity drop corresponds to reduction in speeds as well as increased stop-and-go behavior. The objective of this analysis is to investigate, at the occurrence of traffic stream breakdown or congestion, the behavior of stopped vehicles and how they accelerate until reaching capacity. This would shed some light on strategies and measures needed to reduce the impacts of the capacity drop occurrence as a result of the breakdown phenomenon.

In order to investigate this phenomenon, the concept of capacity needs to be presented generally. Such concept is one of the most debatable issues in the field of traffic flow theory and is mostly presented throughout the speed-flow relationship curve, which consists of an uncongested "stable" branch and a congested "unstable" branch. The ongoing debate is whether the capacity approached from the uncongested flow is higher than that approached from the congested flow, represented as a discontinuous speed-flow curve. Another hypothesis supports representing the speed-flow relationship as one continuous curve, assuming no capacity drop happens. In order to evaluate the concept of capacity at the onset of congestion, some simulation runs are made using

INTEGRATION software [2, 3]. The results of these simulation runs are compared to those results presented in the literature, to examine the possibility of existence of capacity drop after the breakdown occurrence.

Background

The general mechanism of the occurrence of congestion is illustrated throughout the discontinuous speed-flow relationship, where the uncongested branch presents the free flow conditions followed by speed reduction till reaching speed at capacity. Once demand exceeds capacity, breakdown or congestion occurs and queue propagates upstream. Hence, the operation shifts to the congested branch, which presents the unstable operating conditions within the queue and reflects constant queue discharge flow with increasing downstream speeds [4].

The capacity drop issue can be investigated on freeways and also at signalized intersections. On freeways, the congestion takes place at stationary bottlenecks. Examples of freeway bottlenecks are reduction in number of lanes, on-ramp merging into the freeway, or horizontal curve on the freeway. While at signalized intersections, the congestion occurs once the signal turns red and the queue starts to form upstream the intersection stop-line. Once the signal turns green, the resulting queue starts to discharge, where vehicles start moving sequentially. The time until each successive vehicle begins to move is known as the start-loss time [5], which is most for the lead vehicle and diminishes for the following vehicles until the headway becomes constant.

Although the concept of capacity drop on both freeways and signalized intersections is similar, the difference is that on freeways congestion occurs at a time-independent bottleneck. While at signalized intersections the bottleneck is time-dependent, where congestion occurs at the onset of red. Besides, the queue discharge point in freeways is fixed, as each vehicle starts accelerating from the same location at the bottleneck. Alternatively, queue at signalized intersections discharges from a backward moving point where each vehicle starts accelerating from its position in the queue. As the stopping of vehicles during red time at signalized intersections is inevitable, this essay will focus more on capacity drop on freeways.

Some studies, concerning capacity analysis on freeways, have reported a drop in the maximum flow once a queue forms just upstream a bottleneck, whilst others have indicated that no such drop occurs. In 1990 Hall and Hall [6] investigated the effects of formation of upstream queue on flow. It was claimed that there is no reduction in capacity at bottlenecks downstream of a queue and that upstream queue formation had no effect on flow rates [6]. Nevertheless, in 1991, Hall and Agyemang-Duah [7] came back and denied this claim, saying that Hall and Hall [6] did not have enough information to ascertain the queue start times and the flows in the data were not heavy enough.

Later, it was investigated if capacity drop can be related to other measurements or not. Chung et al [8] inferred that increase in the freeway density is always followed by a drop in capacity. Three different bottlenecks on different freeway segments were investigated to examine the relation between the density and the drop in capacity. It was found that the concurrence between a critical density value and the capacity drop was fairly reproducible across days. Accordingly, it was concluded that the increase of density relates to the capacity drop mechanism [8]. Nevertheless, what was concluded is somewhat questionable. Generalizing a fixed critical density value to be applied at any freeway could not be accepted unconditionally, as the capacity drop can result from factors other than increased density. Contrarily, increased traffic density can occur without corresponding drop in capacity. For instance, a sudden lane changing decision from one driver can block a lane and increase its density, while the traffic volume is not high or near capacity. This implies that not only high traffic density can trigger capacity drop, but it should be accompanied by high flow rates. Besides, no deterministic value for density can accompany the reduction in capacity, since the occurrence of breakdown and the corresponding capacity drop is more a probabilistic event. In more than one study, e.g. [9, 10], Kerner investigated the breakdown phenomenon throughout his proposed three-phase traffic theory [11], where he represented the occurrence of breakdown by the transition from free flow phase (F) to synchronized flow phase (S). Kerner [10] agrees that the breakdown is a probabilistic phenomenon , and not deterministic as concluded by Chung et al [8].

Another study by Persuad et al [12] conforms to Kerner's hypothesis, where it was stated that the occurrence of breakdown has a probabilistic nature. The probability of breakdown was found rising by increasing the flow rates, e.g. maintaining the pre-queue flows at the same level as those that occur after a queue forms, makes the probability of breakdown almost negligible. For more increased flows the probability of breakdown rises dramatically [12].

Simulation Analysis

In this section, simulation analyses are made in order to evaluate the concept of capacity drop upon congestion. These analyses were done using INTEGRATION [2, 3]; a traffic simulation software. The results of these simulation runs are presented and compared to those results in the literature.

Simulation runs are made by analyzing the capacity change before and after congestion on a simulated freeway bottleneck. This was done using two different scenarios. Scenario 1 is to allow the vehicles to flow freely by deactivating the bottleneck, whereas scenario 2 is to force vehicles to reduce their speed at the bottleneck location till reaching complete stop. The latter scenario results in a queue forming upstream the bottleneck. The layout of the network used for the simulation runs is shown in Figure 1. It consists of one origin zone, one destination zone, and an intermediate node in between. The network consists of two one-lane links with one-kilometer long each. The vehicles flow from zone 1 to zone 2 as indicated by the arrows in the figure. In the intermediate node a stop sign is introduced, when scenario 2 is applied. Creating the bottleneck through a stop sign in a one lane freeway is because the required bottleneck should satisfy some restrictions. First, all vehicles should be forced to come to a complete stop thus the stop sign was used. Second, this bottleneck should present the bottleneck effect caused by a reduction in number of lanes without the effect of lane changing. The flow in both cases was measured using loop detectors starting from the location of the stop sign till the destination zone at 100-meter spacing, as shown in the figure.

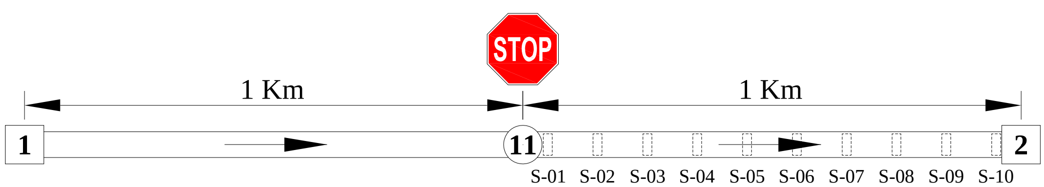

Figure 1: Network Layout for the Freeway Simulation

The first simulation run was made based on a demand of 1800 vph, a free-flow speed of 100 km/h, and speed-at-capacity of 80 km/h. The stop sign was not included in this run to measure the capacity based on uncongested flow. The flow was plotted for the ten stations, as shown in

Figure 2. It is obvious that the flow for the different location is the same and is around 1800 vph. Moreover, Figure 3 shows the speed distribution for the ten stations. It can be seen that the speed at the ten stations is not widely different and ranges between the free-flow speed and the speed-at-capacity.

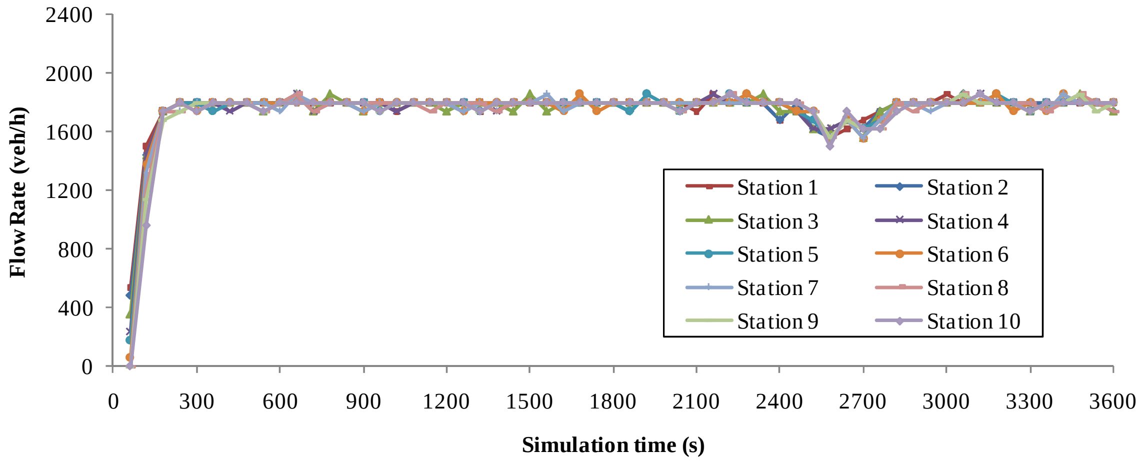

Figure 2: Scenario 1 Flow Rate Distribution at the Ten Stations

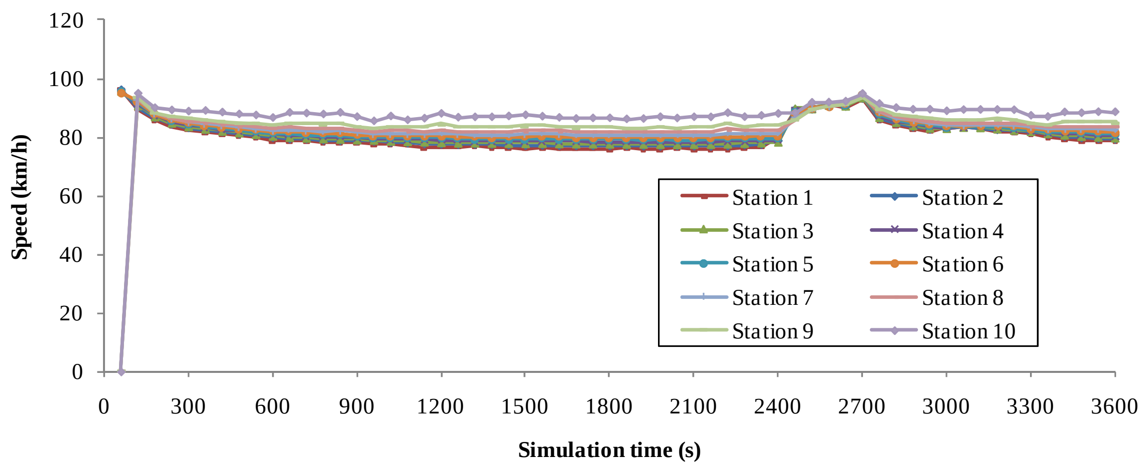

Figure 3: Scenario 1 Speed Distribution at the Ten Stations

Repeating this simulation run, but considering a stop sign to apply the second scenario in order to measure capacity approached from congested flow, the flow was plotted for the ten stations, as shown in Figure 4. It can be observed that the maximum flow is around 780 vph. Moreover, the ten stations yield almost the same capacity, which indicates that the flow in different locations in the bottleneck remains almost constant. However, as shown in Figure 5, the speed varies with location in the bottleneck. It can be concluded from the results that average speed increases while flow remains constant with the progress of the location in the bottleneck. This increase in speed is due to that vehicles accelerate when departing the queue. However, the results from these simulation runs conclude that when vehicles approach from uncongested flow the capacity is higher than when approached from congested flow. This difference in the two capacities confirms the existence of a capacity drop when queue forms upstream a bottleneck. The same simulation runs were repeated but with changing the demand to 2300 vph. The capacity in scenario 1 was found to be around 2300 vph. However, the capacity in scenario 2 was found to be around 780 vph, similar to the previous run. This indicates that when breakdown occurs, maximum capacity could be achieved is less and the same regardless the use of different demand volumes.

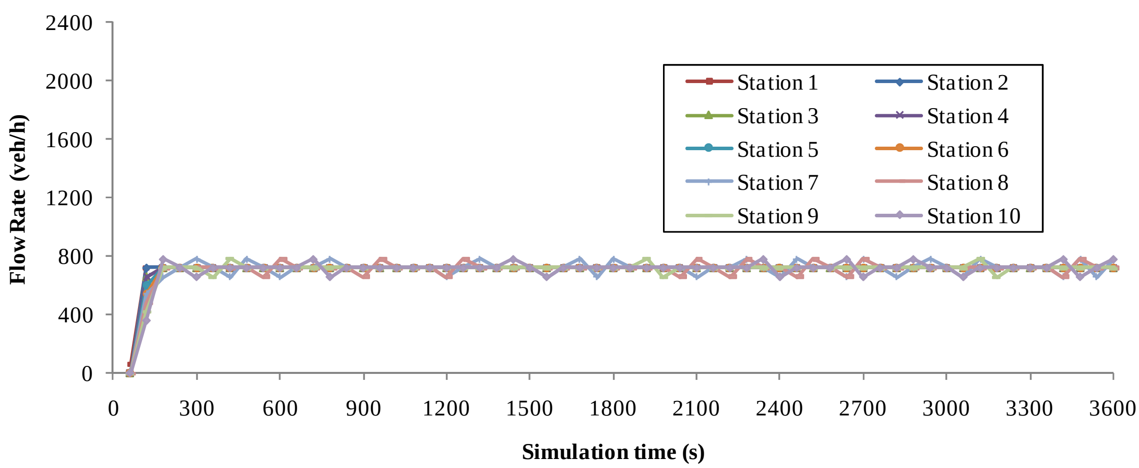

Figure 4: Scenario 2 Flow Rate Distribution at the Ten Stations

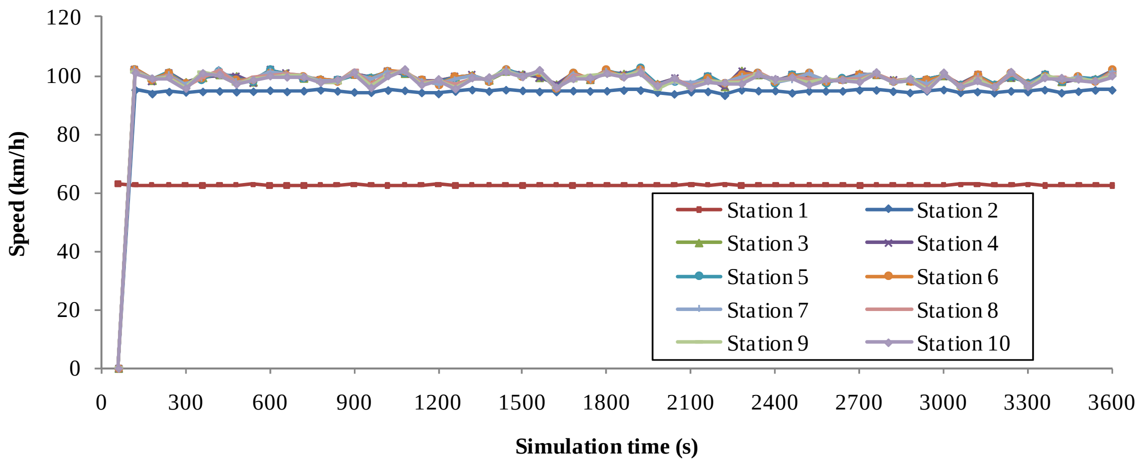

Figure 5: Scenario 2 Speed Distribution at the Ten Stations

Comparing the above results to those in the literature, the results from the simulation runs are consistent to the queue discharge behavior with constant discharge flow and increasing speeds. This also conforms to another study by Persaud and Hurdle [13] which states that the vehicle average discharge speed from a queue varies with the location in the bottleneck.

Conclusions

Transportation, especially highway vehicles, is a main source of polluting emissions. In order to reduce such negative impacts on the environment, the consequences of recurring congestion should be alleviated. Capacity drop, as one of these consequences, is considered one of the most debatable issues in the field of traffic flow theory. In general, capacity drop happens at onset of congestion at freeway, as well as signalized intersections. Capacity drop on freeways has many questionable debates: Does capacity drop exist on freeways or is there no such capacity drop? Is the occurrence of breakdown deterministic or probabilistic in nature? Although results from simulation analyses support theories saying that capacity drop exists on freeways, still more research is needed in order to investigate those contradicting hypotheses and answer questions posed in the literature.

Furthermore, although start-loss at signalized intersections was not covered in this essay, traffic strategies could be achieved in order to reduce start-loss and hence the stopping delays; e.g. countdown timers or flashing green indicators.

Finally, the essay recommends further research to be conducted in order to achieve and examine strategies and measures to reduce the impacts of the capacity drop occurrence as a result of the breakdown phenomenon. In summary, by finding traffic strategies to improve the capacity drop and start-loss, positive impacts on the overall environment would be observed.

References

1. *Expanding Metropolitan Highways: Implications for Air Quality and Energy Use, Special Report 245*. 1995, Washington, D.C.: Transportation Research Board, National Research Council.
2. M. Van Aerde & Associates, Ltd., *INTEGRATION Release 2.30 for Windows: User's Guide - Volume I: Fundamental Model Features*. 2005.
3. M. Van Aerde & Associates, Ltd., *INTEGRATION Release 2.30 for Windows: User's Guide - Volume II: Advanced Model Features*. 2005.
4. Roess, R.P., E.S. Prassas, and W.R. McShane, *Traffic Engineering*. 3rd ed. 2004, Upper Saddle River, N.J.: Pearson/Prentice Hall.
5. Long, G., *Start-Up Delays of Queued Vehicles.* Transportation Research Record: Journal of the Transportation Research Board, 2005. **1934**(-1): p. 125-131.
6. Hall, F.L. and L.M. Hall, *Capacity and speed-flow analysis of the Queen Elizabeth Way in Ontario.* Transportation research record., 1990(1287).
7. Hall, F.L. and K. Agyemang-Duah, *Freeway capacity drop and the definition of capacity*. Transportation research record., 1991(1320).
8. Chung, K., J. Rudjanakanoknad, and M.J. Cassidy, *Relation between traffic density and capacity drop at three freeway bottlenecks.* Transportation Research Part B: Methodological, 2007. **41**(1): p. 82-95.
9. Kerner, B.S. and S.L. Klenov, *Probabilistic breakdown phenomenon at on-ramp bottlenecks in three-phase traffic theory*. Transportation Research Record, 2006(1965): p. 70-78.
10. Kerner, B.S., *On-ramp metering based on three-phase traffic theory downstream off-ramp and upstream on-ramp bottlenecks.* Transportation Research Record, 2008(2088): p. 80-89.
11. Kerner, B.S., *Three-phase traffic theory and highway capacity*. Physica A: Statistical Mechanics and its Applications, 2004. **333**(1-4): p. 379-440.
12. Persaud, B., S. Yagar, and R. Brownlee, *Exploration of the breakdown phenomenon in freeway traffic.* Transportation Research Record, 1998(1634): p. 64-69.
13. Persaud, B.N. and V.F. Hurdle, *Some new data that challenge some old ideas about speed-flow relationships.* Transportation Research Record, 1988(1194): p. 191-198.