Anticipatory Pricing to Manage “Flow Breakdown”

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Extended Abstract

This paper deals with ex-ante pricing to improve the reliability of highway travel time. It is concerned with the phenomenon that traffic engineers refer to as “flow breakdown.” This situation occurs when a highway is close to, but less than, its maximum theoretical capacity as measured in either flow or density. Breakdown occurs when the highway deviates downward off of the standard density-flow relationship. The magnitude of the breakdown appears, in practice, to be quite large. Capacity can fall by up to 30%. The breakdown then persists until inflow has declined (most likely due to nearing the end of the peak period) to such an extent that the highway can return to the “normal” density-flow relationship.

The causes of the flow breakdown are numerous, and include vehicles weaving between lanes, the effects of random excessively slow vehicles, individual aggressive drivers, tailgating, sharp braking, unusual weather, or an unusual visual distraction. The main implication is that flow breakdown is probabilistic in that it does not necessarily occur every day, and that the probability gets larger at higher densities and flows. In our context, flow breakdown does not refer to situations where flow declines due to a backup caused by a bottleneck in a downstream link or due to some or all lanes being closed due to a traffic crash. Both of these situations have been adequately discussed in the literature.

The traditional congestion literature sets prices to deal with regular, predictable congestion when demand exceeds a fixed design capacity. Flow breakdown causes the capacity to fall in a probabilistic manner even if traffic is less than the design capacity. The objective of this paper is to investigate whether congestion prices should be set above those necessary to internalize the “regular” (i.e., non-breakdown) congestion because there is a probabilistic extra externality imposed on future time periods when breakdown occurs. Expressed in different terms, expected outflow (in a given window of time) might be higher if prices were
bid up to reduce inflow because it is lessening the chance that a large and persistent reduction in out-flow may occur as a consequence of breakdown.

The prices we discuss are anticipatory reliability tolls that are set in advance to manage the inflow to a highway in the presence of probabilistic breakdown. The model will have drivers endogenously choosing their departure times based on the price schedule (if a toll is charged) and expected travel times. While one could imagine that ex-post breakdown prices could be charged when breakdown actually occurs, such prices would not be of practical use if drivers have already pre-committed to their departure time and/or if there were not suitable parallel routes that drivers could choose to avoid the affected link.

A version of the standard bottleneck model is developed to model the morning peak including the risk of probabilistic breakdown. A fixed number of single-occupant vehicle drivers travel from “home,” which is located immediately before the bottleneck, to “work,” which is located immediately after the bottleneck. Our model has homogeneous drivers and continuous time. Drivers all have the same desired arrival time at “work” but endogenously choose their departure time from home.

The bottleneck has two capacity states. On “good days” the capacity is sufficient to accommodate the volume of arriving traffic at the bottleneck. So on a “good day” there is no queuing and no delays. But on a “bad day” bottleneck capacity falls and becomes binding on the volume of arriving traffic at the bottleneck. So on a “bad day” there is queuing and delays. The probability of a “bad day” is endogenously determined and depends on the traffic flow. The closer the equilibrium flow is to the bottleneck capacity on a good day the greater is the probability that on any given day breakdown will occur.

Which of these two capacities applies is randomly drawn each morning. Consequently in our model breakdown either happens immediately on any given day or doesn’t happen at all. We model the uncertainty this way because it gives us the relationship we want between the probability of breakdown and the departure rate from home while keeping the model tractable. A more sophisticated but less tractable model would allow for randomness in when breakdown occurs on a “bad day.”
The model is in continuous time. In deciding on their departure time, drivers are aware of the probability of breakdown function and its effects. There is a linear (but not symmetric) penalty function for arriving early or late at the destination. But, on any given day drivers cannot change their plans or deviate from their chosen departure time when the realization of whether a breakdown occurs or not becomes common knowledge (by radio announcement for example).

The model is initially used to determine the departure time schedule in the absence of any pricing. We find that in equilibrium that there will be three groups of drivers.

1. These drivers who choose a departure time such that they arrive early (or exactly on time) on both good and bad days.
2. Those who arrive early (or exactly on time) on good days, and late on bad days.
3. Those who arrives late on both good and bad days.

The model determines the overall length of the peak period, the time windows in which each of these three groups departs from home, and the departure (inflow) rate associated with each group.

We then use the model to calculate a schedule of social welfare maximizing fine tolls, that is to say tolls that can vary continuously across the peak period. There will still be the three groups of drivers identified in the previous paragraph, but the total number of drivers in each group and their departure times will be different from the unpriced scenario. The improvement in welfare from the reduction in total travel time and schedule delay can be estimated, as can the change in the probability of breakdown occurring.

This work has a number of implications for both theorists and practitioners. The model describes a commonly observation feature of commuting, the day-to-day variation of travel time in equilibrium without having to assume stochastic demand. We also have a group of drivers who generally arrive early or on time, but occasionally arrive late. This is also a commonly observed feature of commuting. This model is also consistent in equilibrium with the empirical observation by traffic engineers that highways close to capacity can deviate from a unique stable density-flow relationship.

For the point of view of practitioners who may have to set toll schedules, we have modelled a situation where on “good days” traffic flows are less than the capacity of the highway and no travel delays occur. If one just considered these days, drivers would not suffer any travel delays and congestion tolling would not
be required. However, we have introduced the (endogenously determined) probability that “bad days” also occur, and have set a toll schedule that improves overall welfare even though drivers will pay a congestion toll on days when travel delays do not actually occur.