QUALITATIVE CHANGE WAVES – THE AUTOMATIC DETECTION OF HIGHWAY TRAFFIC INCIDENTS

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ABSTRACT

The interpretation of traffic sensor readings is an important practical domain for which the current theories are inadequate, and for which the current level of performance is not acceptable. We have used qualitative physics to develop a new traffic model. The model describes the propagation of qualitative variations in the traffic flow. The variations move downstream or upstream like waves and interfere with each other and with local changes in the capacity of the highway. On the basis of that model one can build an inexpensive system that is able to discriminate in real time between recurrent congestions, incidents that require immediate intervention and sensor failures.

1. The problem

The most common traffic sensing equipment is the inductive loop, that mesures the traffic flow (vehicles/hour) and the occupancy (percent of the total time during which a vehicle is

present above the loop). More sophisticated sensors can mesure the speed of each vehicle. Each sensor covers one lane, and the sensors are arranged in cross sections before and after each exchanger, and sometimes on the access ramps. The inductive loop and traffic sensors in general are discussed in (1). Such an installation can involve as many as 3000 sensors, and provide a complete set of readings every minute.

The interpretation of the readings is not easy. The sensors are not fully accurate and prone to intermittent failure. Currently there is no program or humain expert that can discriminate in real time on a routine basis between incidents that require immediate assistance, congestions and sensor failures. For a discussion of current algoritms and systems, see (2). Beware of the very common confusion between ^congestion detection^, which is relatively easy, and ^incident detection^. Since there is not much expertise, an automatic system must rely on a deep model of the traffic process.

2. Classical traffic models

There is currently a wide agreement on a model that describes the relationship between the maximum capacity of an highway lane and traffic speed as a curve that goes through a maximum of 2000 vehicles/hour for a speed of 35 miles/hour. At higher speeds, the cars are too for apart and at lower speeds, they are too slow. The exact shape of the curve and the position and value of the maximum vary with many parameters, including the width of the lanes, the slope of the highway, visibility and

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weather conditions. Below the optimum point, the occupation is high, beyond 15 percent, and the traffic is ^congested^. Above the optimum point, the occupation is below 10 percent, and the traffic is ^not congested^.

The model is described in (3). It is well supported by the mesurements that plot observed flow against observed speed across a given lane cross section. However, the usual interpretation of the curve is debatable. The common belief is that the **cause** of the reduced maximum capacity is the reduced speed.

A more carefull examination of the experimental situation shows that another explanation is possible, namely that°
- the maximum capacity of highways below 35 miles/hour is independent of the speed
- downstream from the cross section where the lane capacity is mesured, there is a reduction in total highway maximum capacity, such as a reduction in the number of lanes
- the total flow upstream is equal to the flow that can leave the constriction downstream. That flow is distributed across the available upstream lanes.

That idea is put forth in (4), where the author has mesured cars leaving the constriction downstream at the speed of 20 miles/hour, with a capacity of 2150 vehicles/hour/lane, in the range of the maximum capacity that can be attained only at 35 miles/hour according to the classical model.

To get an estimate of the maximum free flow capacity at lo[w]
speeds, we have mesured the flow leaving the queue at a traf[fic]
light, with an empty road ahead. We started counting at r[ed]
when the light turned green, and stopped when the last car [of]
the queue had crossed, at about 35 miles/hour. The mesu[red]
capacity was 1914 vehicles/hour, which is again in the 2[000]
vehicles/hour range.

3. The flow model

The main hypothesis of the flow model is that a reduction [in]
speed will never force a reduction in flow. The flow in a cr[oss]
section is then controlled°

– either by what comes from upstream, everything that comes
can pass through, the free flow situation

– or by what can leave downstream, everything that can p[ass]
through is replaced, the forced flow situation.

We make the second hypothesis that those two flow sta[tes]
correspond to the states identified in the classical model[s on]
the basis of occupation° below 10 percent no congestion [and]
free flow, above 15 percent congestion and forced flow, [in]
between undecided.

4. The origin of congestions

If a speed reduction cannot force a flow reduction, [a]
congestion can be caused only by a capacity limit° [an]
absorption limit at the end of the highway or at an exit[,]

fixed limit on the highway such as the number of lanes or a variable limit that appears as a consequence of an incident.

In the following exemples, t0, t1 and t2 are three consecutive instants in time. We plot the flow as a function of position along the highway, and the congested flow is hatched. The cross represent the position and the level of a capacity limit. Traffic flows from right to left.

t0   t1   t2

fixed limit in increasing traffic

t0   t1   t2
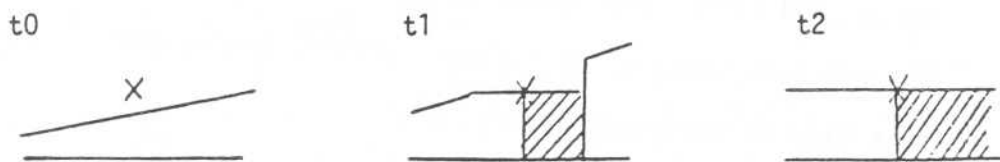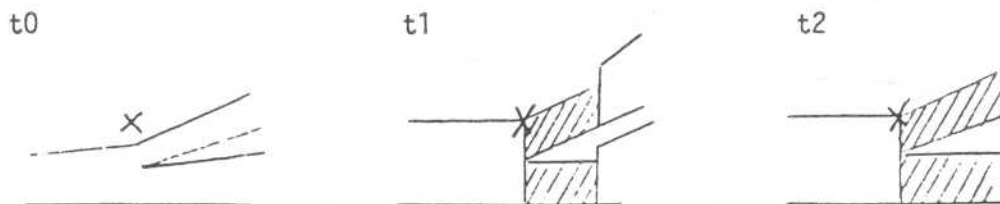
fixed limit in increasing traffic - access ramp

t0   t1   t2
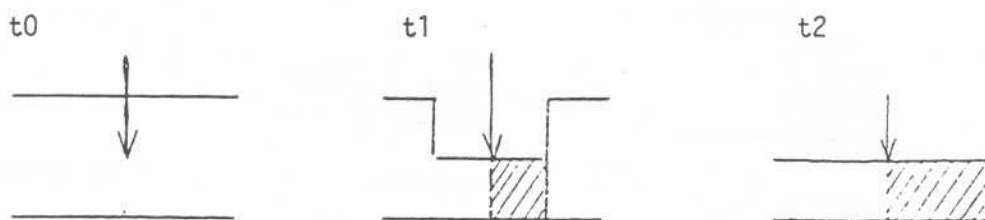
installation of a variable limit

5. Waves of change

As can be seen from the exemples above, we are interested in the onset and propagation of discontinous changes in the traffic flow. Those changes might consist in°

- a ^positive step^ or a ^negative step^ in the flow

- a change in the time derivative of the flow, that varies between ^positive^, ^zero^ and ^negative^

They might be associated with a change of the congestion between ^yes^, ^no^ and ^undeterminate^.

Those discontinuous changes propagate like a wave. In the discussion below, we will concentrate on the ^flow step^ waves, and ignore the ^undeterminate^ value for the congestion. The complete study gives similar results. The possible waves in free flow or congested traffic are°
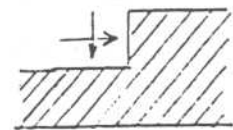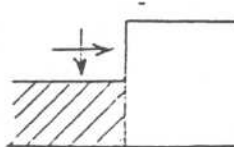

downstream   downstream   upstream

positive step   negative step   negative step

The possible waves at a congestion border are°
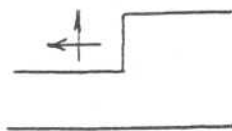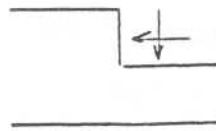
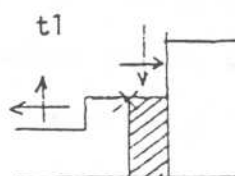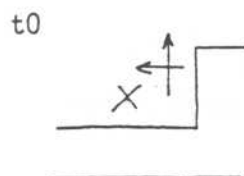upstream   downstream   upstream
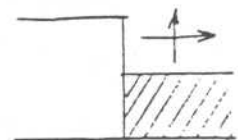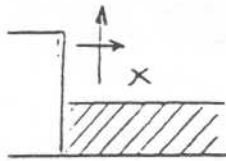
negative step   negative step   positive step

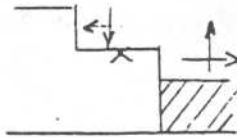## 6. Interference between waves and capacity limits

Only the increase wave can interfere with capacity limits, so that the following two evolutions are possible
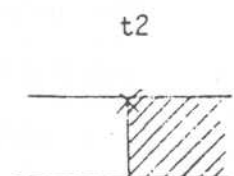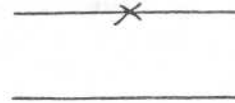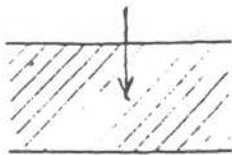
t0   t1   t2
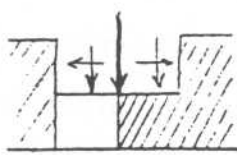
and t0   t1   t2

7. Onset and removal of a variable capacity limit
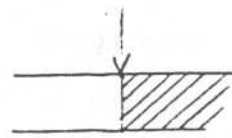
There are 5 onset cases, for instance

t0   t1   t2
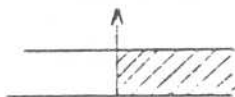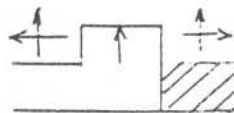
A simple removal is

t0   t1   t2
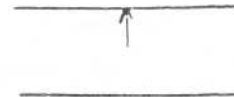
8. Interference between waves

Some waves cannot physically meet, like an upstream positive step at a congestion border and a downstream increase wave in non congested traffic. Among the waves that can interfere, we show an upstream border positive step and a downstream border negative step.
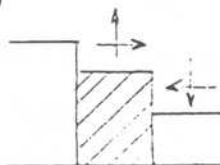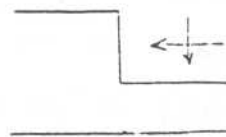
t0   t1   t2

9. Incident detection

The initial problem can now be rephrased as the discrimination between sets of waves caused by a fixed capacity limit, sets of

waves caused by a variable capacity limit and nonsensical sets of waves that correspond to sensor failures.

The sensor data of each cross section can be analysed to detect the waves that go through it, and the waves detected at consecutive cross sections can be put in relation. The dir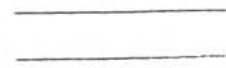ection of propagation of a wave can be determined from the readings at a single cross section. If we consider what a cross section senses before and after the passage of each of the waves described in 3.3, we have the following table°

congestion before	congestion after	wave step	wave direction
no	no	any	downstream
yes	yes	negative	upstream
yes	yes	positive	sensor fail.
yes	no	negative	downstream
yes	no	positive	upstream
no	yes	negative	upstream
no	yes	positive	sensor fail.

We can now indicate how to discriminate between the first exemple of 3.2 that describes the onset of a congestion at a fixed capacity limit, and the third exemple that describes the onset of a congestion at a variable capacity limit.

In the fixed case, the downstream cross section, to the left, will see a change in the flow derivative from ^positive^ to

^zero^. In the variable case, it will see a ^negative step^ in the flow.

The upstream cross section will see a ^negative step^ in both cases, but the step will tend to be lower in the fixed case, since it takes back only the increase in upstream traffic that has continued during the propagation of the congestion.

In both cases, the final values of the flow at both cross sections after the passage of the two waves will be equal to each other and to the capacity of the limit.

We can also see that the reaching of a fixed limit or the onset of a variable limit can be detected very fast on the basis of the downstream wave, that travels at the free flow vehicle speed, rather than on the basis of the upstream wave, that travels at the much lower vehicle accumulation speed. The classical model relies on the equivallent of the upstream wave.

10. Implementation issues

Beyond the fact that the flow model has a causal explanation and fits the data better, it has two major advantages over the classical model

- it does not need any description of the highway segments. The capacity limits are detected in operation and the distances on the highway between consecutive sensor cross sections are not

used.

— it makes direct use of the occupancy mesure, which is cheap to make, rather than the speed mesure, which is more expensive. Also, it and does not rely too much on the accuracy of the occupancy mesure, which is not very good. The methods that use speed need accurate data.

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