Ramp Metering, Speed Management and Braess-like Paradoxes

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1 Introduction

Control measures introduced to improve traffic performance in traffic motorway include ramp metering and speed limit control.

The potential of ramp metering for alleviating freeway congestion is widely recognized and documented, Haj-Salem and Papageorgiou 1995. Most existing ramp metering studies are based on local traffic-responsive control strategies, such as the percent occupancy strategy, the demand-capacity method and the linear feedback strategy ALINEA. Coordinated ramp control has also been studied, Zhang *et al*. 1996, Haj-Salem and Mangeas 1998.

Speed management aims at homogenizing the practical speed along motorway sections and at minimising the number and the severity of accidents and thus increasing safety and delaying the onset of the congestion. The potential for traffic control of speed management has been recognized by some authors, Smulders 1990.

The paper investigates the origin of the gains resulting from ramp metering and speed management.

Similar to Braess's paradox (Braess 1968, Pas and Principio 1997), both traffic control methods reduce the nominal capacity in order to achieve gains. Ramp metering and speed control are shown to prevent capacity drops from which the system is unable to recover, due to hysteresis. This is the main origin of the gains. This phenomenon is explained by taking into account the upper bound on car acceleration (Lebacque 2003 a) and by modelling congestion in intersections. A simple intersection model based on first order macroscopic traffic modelling and the local traffic supply and demand concept (Lebacque 2003 b), is introduced in order to explain intersection capacity drops. It is also shown that by combining both control strategies, greater gains can be achieved, and that improvement of traffic flow can be expected even in congested quasi-static situations. Further, gains increase with the distance to the onramp or the area subject to speed control. Thus earlier findings (Lebacque and Haj-Salem 2001) are confirmed.

2 Braess paradox principle

The Braess Paradox is described in Braess 1968, Pas and Principio 1997. It is a static assignment paradox and applies to networks at equilibrium. In its simplest form, the paradox in the original Braess network can be stated as follows: by suppressing some unfavourable arc, travel times of all users are decreased. An "unfavourable" arc connects two demand sensitive arcs belonging to different paths. The paradox is believed to be largely prevalent in real networks.

Why does a decrease in nominal capacity lead to an increase in actual capacity, and to the improvement of both total cost and individual costs? The explanation is that some path costs do not increase with path demand, as expected. The dynamic analogue would be hysteretic cycles in traffic flow, in which a decrease in demand does not imply an increase in capacity. As in the static case, such a situation occurs when traffic demands are "connected", which should not be connected. For instance, excessive demand peaks at a merge can induce a capacity drop in the merge through congestion.

In the static case, disconnection of unfavourable demands is carried out at the spatial level, by increasing the costs of the connecting arcs or by suppressing them. In the dynamical case, disconnection of unfavourable demand peaks is achieved out temporally, which is the aim of ramp metering and speed control.

3 Traffic dynamics

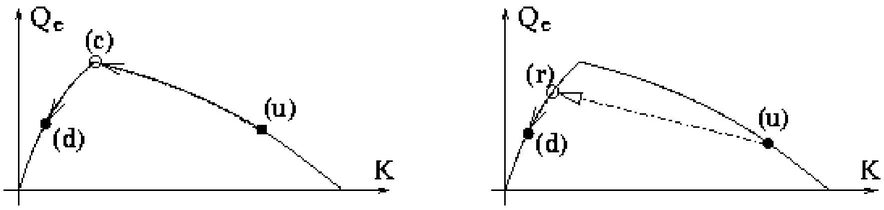
They are based on the first order LWR (Lighthill-Whitham-Richards) model, Lighthill-Whitham

1955, Richards 1956. The basic macroscopic variables are the flow Q, the density K and the speed V, assumed to be a function of position x and time t.
The LWR model can be expressed by the following equations:

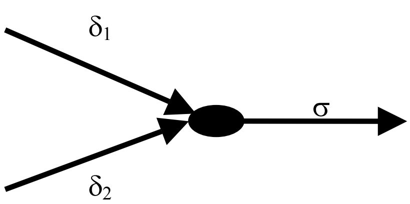
$$\frac{\partial}{\partial t}K + \frac{\partial}{\partial x}Q_e(K,x) = 0 \quad \text{and } Q = KV = Q_e(K,x),\ V = V_e(K,x)$$

with Q_e the fundamental diagram. For numerical solution we refer to Lebacque 1996. The numerical solution is incorporated into METACOR, Elloumi *et al.* 1994 and Haj-Salem and Lebacque 2002.

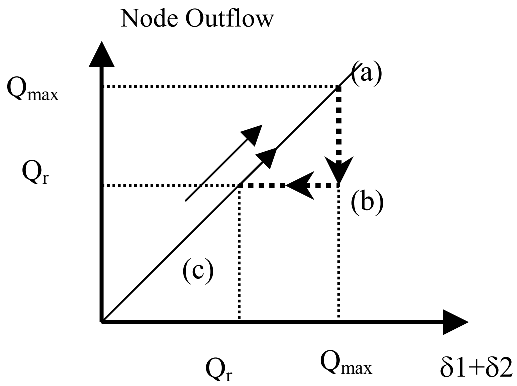
The original LWR model is modified by taking into account the upper bound on vehicle acceleration, Lebacque 2002 and Lebacque 2003a. The effect of which can be illustrated by the following figure:

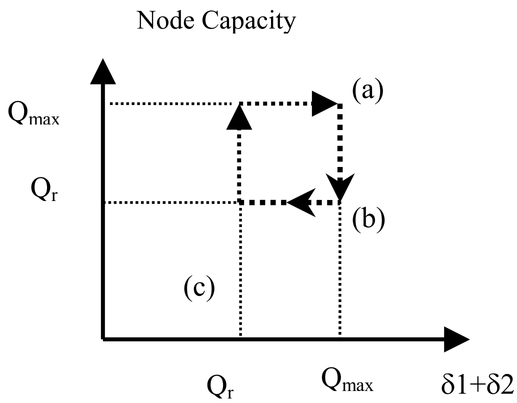


They depict, on a fundamental diagram, two traffic states **(u)** and **(d)** representing an upstream congested traffic state and a downstream fluid state. The LWR model predicts that traffic accelerates from **(u)** to **(d)** with an intermediate state **(c)** for which flow is maximum. Its has been observed in the literature that this property of the LWR is incompatible with ramp metering benefit (Haj-Salem and Papageorgiou 1995) which is why ramp metering schemes are generally applied with second order models only. If we consider the prediction of the Bounded Acceleration LWR model, the transition between **(u)** and **(d)** will follow the **(u)** → **(r)** line with the intermediate (*recovery*) state **(r)** at a much lower outflow level. The ratio Q_r/Q_{max} is of the order 5/7 in accordance with Kerner's observations. The above model implies that the appearance of congestion leads to capacity reduction.
The same concept is applied to intersection modelling.



For merge, we define upstream flow demands δ_1, δ_2, downstream suply σ , and capacity Q_{max}. Traffic supply and demand in the context of intersections are introduced in Lebacque 1996, Lebacque and Khoshyaran 2002.





If $\delta_1 + \delta_2 > Q_{max}$, the node is congested, and the capacity drops to the recovery flow (Q_r). This outflow is maintained at the lower Q_r level as long as the demand $\delta_1 + \delta_2$ exceed this value.

4 Control

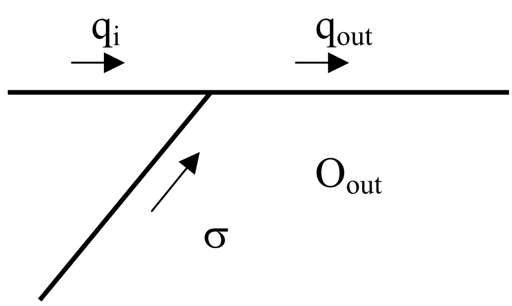
Speed Control : the speed control aims at homogenising the practical speed along the motorway sections and can be conceived, when it is active, as limiting the outflow of the system below an upper bound Q_{lim}.

If the density is K, this aim can be achieved by imposing a limit speed expressed by $V_{lim} = \frac{q_{lim}}{K}$.

Such a scheme is feasible only if the speed limit can be imposed at constant density, which means that the speed message signs (SMS) must be seen by all drivers. The distance between two consecutive SMS should be about 500 meters.

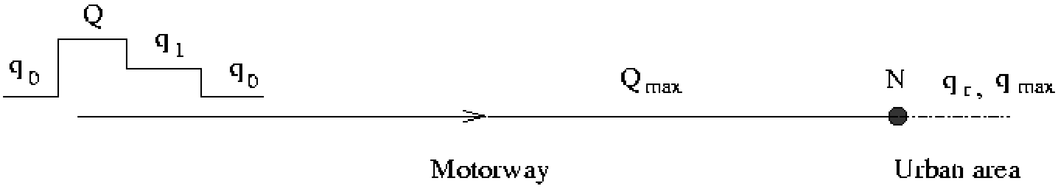
Ramp Metering : we assume that ramp metering is achieved through a local traffic responsive strategy such as ALINEA.

ALINEA aims at keeping the merge in a fluid traffic state by limiting the onramp outflow.
It is designed to prevent node congestion and consequently the node capacity drop is avoided. A limiting factor for the application of ALINEA is the minimum guaranteed outflow Q_{min} of the on-ramp.

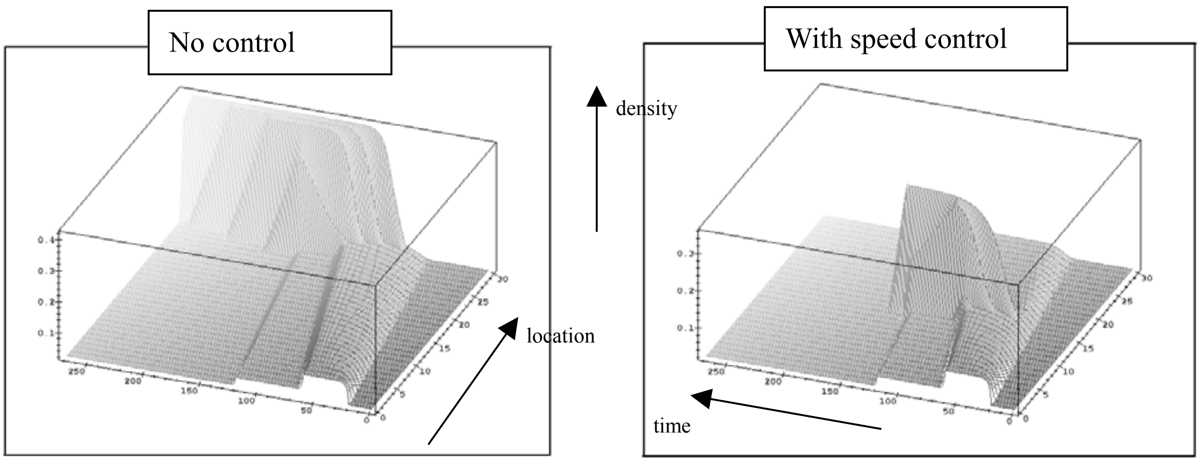


5 Results

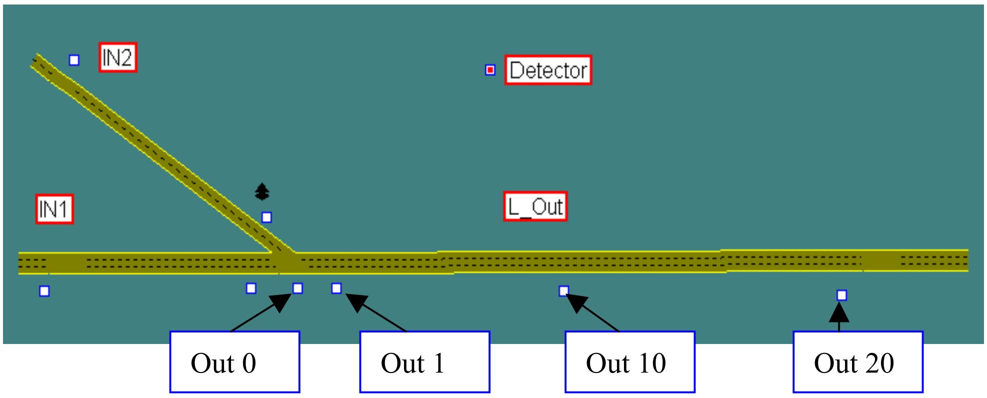
Speed control:
The following situation is considered



A traffic peak enters the motorway which terminates in a urban zone. The interface between motorway and urban zone is modelled as a node with capacity q_{max} and recuperation flow q_r. Themotorway has a capacity Q_{max}. It is assumed that $q_0 < q_r < q_1 < q_{max} < Q < Q_{max}$. The aim of the control is to keep flow on the downstream part of the motorway below the maximum inflow of the urban zone, q_{max} , in order to prevent a capacity drop to q_r. In this example control is applied on the downstream half of the motorway only. The results are the following (plots of density vs. location and time), showing a general reduction of congestion and no queuing at the entrance of the urban zone. The cumulative inflow and outflow show a gain for all users.

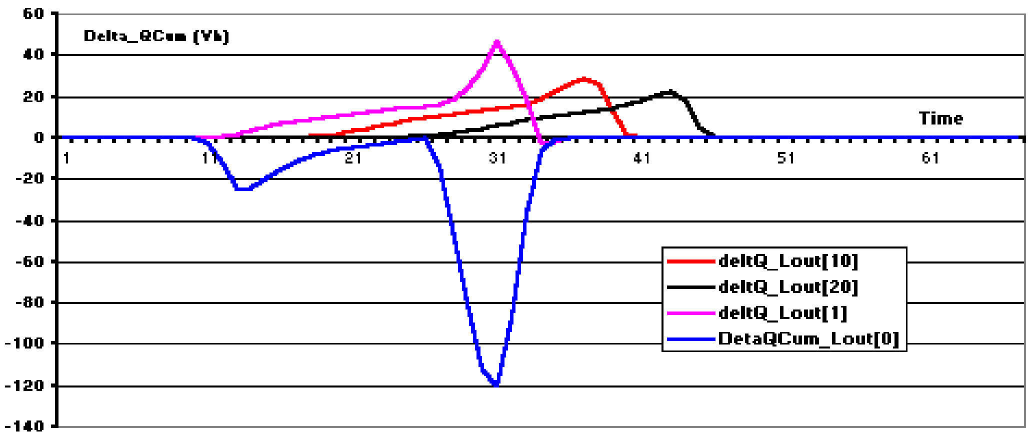


Ramp metering
We consider the following merge:

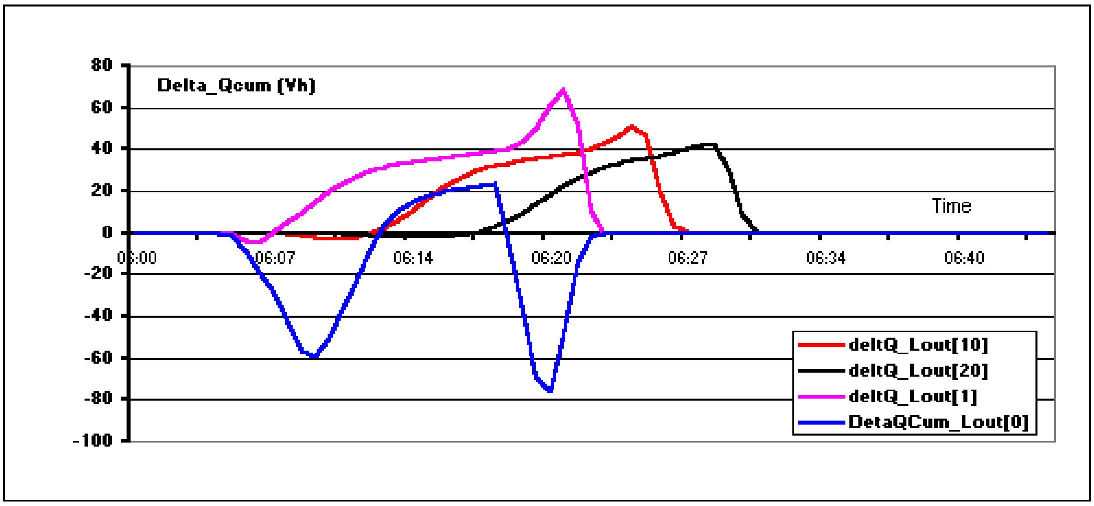


ALINEA is applied on onramp IN2. Demand is constituted of two simultaneous traffic peaks, on IN1 and IN2, of duration 15 mn, resulting in a node inflow exceeding the node capacity.
The figure below shows the difference between cumulative flows with and without ramp metering at locations OUT_0, OUT_1, OUT_10, OUT_20. Outstanding features are:

- Gains (but not all users at all times), except inside the intersection (location OUT_0)
- The gain increases with distance (confirming findings in Lebacque J.P., H. Haj-Salem. 2001). Gains in speed amplify with distance.



If ramp metering is applied on the onramp IN1 and speed control is applied on the motorway IN2, delaying the arrival of the platoon on IN2, the results are definitely improved



The principle is the same as in the Braess paradox example: ramp metering and speed control reduce the interaction of the platoons, reducing the capacity drop in the node and the resulting velocity decrease. Any gain in velocity has a cumulative effect over distance.

The effect of ramp metering on the node capacity is antagonistic with its effect on the onramp traffic. With ramp metering, the onramp traffic becomes more congested, resulting in reduced onramp outflow (bounded acceleration effect). Hence the importance of the lower flow bound on the onramp, already noted experimentally (Haj Salem H., M. Papageorgiou. 1995).

6 Conclusion

The paper, relying on a simple traffic flow model (Bounded Acceleration LWR) and a supply-demand based intersection model, shows that ramp metering and speed control improve traffic flow according to principles related to the Braess Paradox concept. The main idea is to increase effective capacity while reducing nominal capacity, by preventing unfavourable interaction of traffic demands. In the dynamic case of traffic management, this means to prevent capacity drop by introducing delays in the traffic flow. The advantage of combining ramp metering, and speed control is explained. Other important facts are pointed out: some limitation of ramp metering, the importance of defining the bounds of the system in order to properly evaluate user gains, the origin of the gains of ramp metering and speed control.

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