Integrated Traffic Flow Control in a Connected Network

PI: **Professor Petros Ioannou**
Electrical Engineering Department,
University of Southern California, EEB200B, Los Angeles, CA 90089-2562
Email: ioannou@usc.edu

Project Objective

Highway congestion due to incidents and bottlenecks is a frequent phenomenon in most Urban highways. Understanding the mechanisms of congestion and finding ways to better control traffic flow in order to prevent or better manage congestion will have a significant impact on travel times, fuel savings and emissions. The project objectives are to design, analyze and evaluate traffic flow controllers to deal with congestion during incidents and bottlenecks for all possible demands and roadway characteristics. The specific objectives are: Design effective lane change controllers which will recommend vehicles to change lanes early enough before reaching the bottleneck or the incident; Develop variable speed limit controllers and combine them with lane change control in order to smooth traffic flow upstream bottlenecks and incidents; Combine the variable speed and lane change controllers with ramp metering control; Demonstrate the effectiveness of the integrated lane change/variable speed/ramp metering control using microscopic traffic simulation model of I-710.

Problem Statement

Highway congestion is detrimental to traffic mobility, safety and the environment. Numbers of studies have been conducted in an effort to avoid or relieve highway congestion with different traffic flow control strategies such as Variable Speed Limit (VSL), Ramp Metering (RM) and Lane Change (LC) recommendation and their combinations. While consistent improvement on traffic safety is reported under existing traffic flow control strategies in macroscopic and microscopic simulations, the results are rather controversial when it comes to improvements on traffic mobility and environmental impact, especially in microscopic simulations. Some researchers attributed these inconsistencies to the complexity of underlying reasons of congestion and highly disordered and stochastic behavior at the bottleneck. Investigating and understanding the dynamical behavior of the open-loop traffic flow system under all possible demand levels as well as initial densities is of great importance in developing approaches for controlling the traffic flow in order to reduce congestion.

Research Methodology

Our methodology is based on a mathematically rigorous analysis of traffic behavior during incidents and bottlenecks. We use the well-known cell transmission model to identify all the flow/density equilibrium states as a function of the traffic demand. When the demand is low an incident such as a closure of a lane or a bottleneck will not have a significant impact on traffic flow which reaches a unique equilibrium state in the low density region. As the demand increases the flow may settle to one of multiple equilibrium states depending on the initial density. As the demand increases above the capacity of the bottleneck the flow saturates and becomes heavily congested. Our methodology is to first understand this dynamical behavior when no controls are applied and use this understanding to develop traffic flow control techniques so that the traffic flow converges to an equilibrium that is the best possible for a given demand. For example when the demand is higher than the bottleneck capacity we would like the traffic flow controller to guarantee convergence of the flow to values very close to the bottleneck capacity. We use Lyapunov and nonlinear techniques to analyze and develop traffic flow controllers which include a combination of lane change, variable speed limit and ramp metering control. Despite the considerable efforts in the design of such controllers our methodology is unique in the sense that it relies both on rigorous analysis and simulation evaluations in contrast to past efforts where adhoc control techniques are used without any theoretical guarantees.

Results

One of the significant results of this effort is to explain the phenomenon of capacity drop during an incident and/or bottleneck and use it to motivate the design of lane change controller. The following figure 1 describes what happens when a center lane closes due to an accident.

The vehicles coming from upstream are not aware of the closed lane till they come very close to it and are forced to slow down or even stop. Then they force themselves in the higher speed open lanes which they force to slow down leading to a throughput right after the incident that is well below the capacity of the bottleneck. Once this phenomenon is understood we design a lane change controller that it recommends lane changes from the upcoming closed lane to the open lanes while the vehicles are in motion and have enough time to perform the lane change. The distance from the incident where the vehicles are instructed to change lanes is very crucial for getting the best performance and is a design control variable that depends on the demand and number of lanes closed.

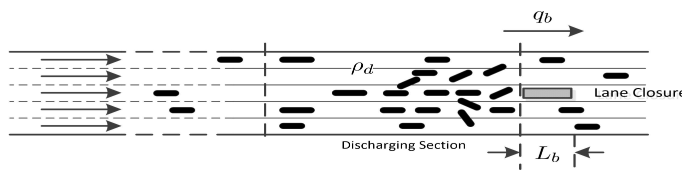

Figure 1 Capacity Drop due to lane closure

While lane change control can eliminate capacity drop, as the demand increases above the capacity of the bottleneck congestion is unavoidable making the bottleneck throughput much lower than its capacity. The best performance is achieved in this case if the incoming flow to the network is reduced to that of the bottleneck capacity. One way to control the inflow from ramps is via ramp metering however controlling the flow from the main lines is more challenging as the use of traffic lights is not feasible. In our approach we control the flow using VSL control which has a nonlinear relationship with the incoming flow hence the use of nonlinear control techniques. Our analysis shows that the proposed combined LC, VSL and RM control guarantees convergence of the flow to the best possible value which is theoretically equal to the capacity of the bottleneck when the demand exceeds capacity. We simulated the proposed controllers on I-710 where one of the 3 lanes is closed for 30 minutes. Table 1 shows the results for two different demand values in terms of travel time T_t, number of vehicle stops $\tilde{s}$, number of lane changes $\tilde{c}$, emissions NOx, CO2, energy (fuel), and particle pollutants PM25. Table 1 compares the case of no control with that of LC only, VSL only and combined control case. It is clear that the combined LC and VSL achieve the best results.

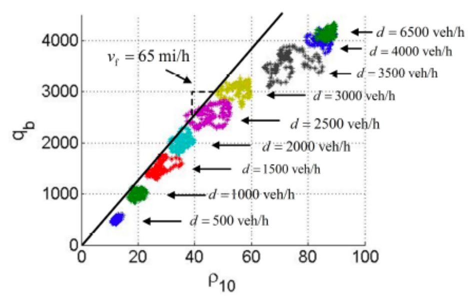

Figure 2 Flow density equilibrium states for

Table 1: Evaluation Results

Demand	6000 veh/h					6500 veh/h				
Control	No Control	LC Only	VSL Only	Control	Improvement	No Control	LC Only	VSL Only	Control	Improvement
T_t	18.85	17.12	18.95	16.85	-10.59%	20.72	17.67	21.21	16.83	-18.76%
$\bar{s}$	11.16	2.45	3.61	1.90	-83.00%	12.10	2.55	3.78	1.91	-84.21%
$\bar{c}$	4.00	4.75	4.74	3.78	-5.60%	4.67	5.54	5.88	4.31	-7.71%
NOx	1.56	1.49	1.61	1.49	-4.43%	1.64	1.58	1.60	1.53	-6.71%
CO2	558.56	543.22	577.59	536.01	-4.04%	589.46	556.47	605.59	537.21	-8.86%
Energy	178.65	173.67	184.76	171.40	-4.06%	186.78	177.93	193.73	170.31	-8.82%
PM25	0.049	0.048	0.047	0.050	0.66%	0.054	0.054	0.053	0.050	-7.73%

The significant reduction of number of stops has an indirect positive impact on safety as well as on the environment and driving comfort. Figure 2 shows the results of Monte Carlo simulations for different demand levels. This research demonstrates the significant impact that traffic flow control could have in managing congestion during incidents and bottlenecks.