Traffic Management: An Outlook

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Abstract

Traffic congestion is caused by inefficient road management and by excess demand. Inefficient management is pervasive. Most urban streets and freeways do not have traffic sensing infrastructure, so one doesn't know how much congestion there is, its cause, or whether meliorative projects are effective. Inefficient road management must be replaced by effective feedback control of signals at intersections and at on-ramps. These control techniques are well known, and they have been successfully implemented in many parts of the world. The investment in sensing needed to implement these techniques is trivial compared to the benefits of an efficiently operated road system. Excess demand must be throttled by demand management. Empirical analysis of popular approaches such as HOV and HOT lane management show they are ineffective except on freeways that are inefficiently managed. New ITS technologies, such as 'integrated corridor management' systems, appear to be founded on quicksand in the absence of a sufficient measurement system. More interesting in the long run could be initiatives that seek to shift modes, such as bicycle and exclustive bus lanes, delivery services for lunch and groceries that may reduce automobile trips, ridesharing, and telecommuting.

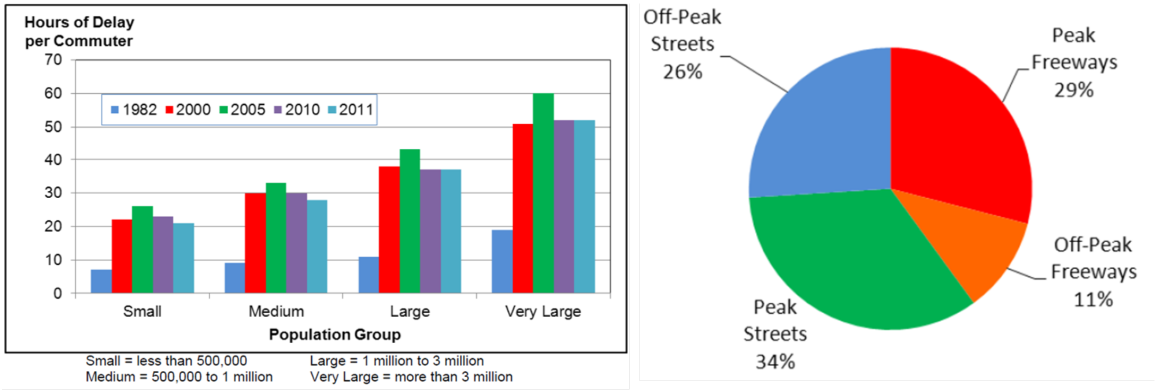
Keywords: traffic control, inefficient management, value of time, HOV, HOT, congestion pricing, managed lanes, autonomous vehicles, integrated corridor

1 Context

Urbanization is accelerating, with population in 500 cities exceeding 1M. The population increase is accompanied by an even faster growth in automobile ownership. World vehicle sales reached 81.8M in 2012 as double-digit growth in North America and the Asia-Pacific region (with 21.4% and 43.6% respectively of global sales) overcame the downturn in Europe and slow growth in South America. Vehicle sales are forecast at 100M in 2018. Since vehicle ownership grows twice as rapidly as income in $3,000-$10,000 per capita range [16], growth in emerging economies is predictable: China, the world's largest market will grow at 5%, and India may surpass Japan as Asia's No. 2 vehicle market by 2016.

In both advanced and emerging economies cities are experiencing worsening congestion as transportation authorities confront the task of maintaining (let alone improving) the performance of their existing road networks. With very rapid growth in the demand for personal transport and freight, the challenge in emerging economies is more severe. Automobile pollution is endangering health, and the environment may be unable to withstand this deterioration.[1] But so long as the powerful can protect themselves from the environment, governments may not take the steps needed to improve the environment.

US Congestion The Texas A&M Transportation Institute (TTI) Urban Mobility Report [45], finds that congestion forced urban Americans to travel 5.5 billion hours more and waste 2.9 billion gallons of fuel at a cost of $121 billion in 2011. Figure 1 shows a trend and congestion share by road type. Thanks to the recession, the 2011 congestion is below the 2005 peak, but it is higher than in 2000 and will increase as the economy improves. Congestion cost rose from $24 billion in 1982 to $94 billion in 2000 (2011 dollars), and will likely increase 40% by 2025.



(a) **(b)**

Figure 1: Congestion statistics: (a) congestion trend; (b) percent of delay by road type. Source: [45].

The TTI report emphasizes that "*the best speed data is combined with the best volume information to produce high-quality congestion measures*," but it places no confidence bounds on these measures. This is unsurprising: TTI combines speed data from a private company and volume data

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[1] A widely-quoted 2013 PNAS paper estimates that total suspended particulates in the air will reduce the life span of 500M in Northern China by 5 years. The particulate estimates in the study are from coal burning, but both gasoline and diesel vehicles emit particulates and GHG.

from Highway Performance Monitoring System (HPMS) files assembled by the Federal Highway Administration (FHWA). The two sets of data are obtained at different times and from different locations, neither provides error estimates, and as TTI does not have the raw measurements, it cannot calculate any confidence bounds.

We know of no city that systematically (say once a month) measures traffic volume, occupancy and speed (VOS) on its main streets. With the exception of a few states like California, most states do not have dense freeway VOS measurement. So when local, state and federal transportation agencies discuss the magnitude and causes of congestion, their discussions lack reliable empirical understanding. Agencies and the press merely selectively repeat the TTI Report, and no one remarks on the absence of reliable measurements.[2]

The absence of reliable traffic measurements means that no one knows how much congestion there is (or whether it is getting worse) in their neighborhood, city or state, which hinders awareness and blunts citizens' motivation to denounce or applaud a transport agency's performance. For example, in 2006 California voters approved 61%-39% a $20B bond measure (Prop 1B) for projects "to relieve congestion, improve the movement of goods, improve air quality, and enhance the safety and security of the transportation system." While one can readily find online descriptions of Prop 1B-funded projects, it is not possible to learn how much congestion relief these projects have provided.[3]

Another damaging consequence of the absence of traffic measurements is that it obstructs accurate diagnosis of the causes of congestion in a particular time and place, and thwarts effective design and implementation of congestion relief projects and reliable project evaluation.

2 Excess Demand or Poor Management

In its online publication "Describing the Congestion Problem [27]," FHWA notes that "the process of congestion relief begins by understanding the problem," and asserts that "highway congestion, very simply, is caused when traffic demand approaches or exceeds the available capacity of the highway system." It also offers a different definition of congestion as 'performance reduction': "congestion . . . represents the difference between the highway system performance that users expect and how the system actually performs." The congestion delay in the TTI report and in the California PeMS system [5] are estimates of the additional vehicle hours spent traveling below a nominal or free flow speed, e.g. 45 mph. Thus, both use 'performance reduction' as congestion measures.

The Joint Transport Research Centre of the Organization for Economic Cooperation and Development (OECD) offers three definitions [37]: (1) it "is a situation in which demand for road space exceeds supply"; (2) it is "the impedance vehicles impose on each other, due to the speed-flow relationship"; and (3) it "is linked to the difference between the roadway system performance that users

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[2] An example: "In the [TTI] Report San Francisco Bay Area ranked as the third most congested region in hours of delay caused by congestion" [3, p. 8].

[3] There is a particular irony here. The California Department of Transportation (Caltrans) in its public presentations on Prop 1B emphasized the importance of Intelligent Transportation Systems (ITS) technologies and their reliance on a ubiquitous and reliable traffic measurement system. However, the California Transportation Commission (CTC), which disburses Prop 1B funds, essentially zeroed out the Caltrans request for the measurement system. So Caltrans, CTC and the public continue to be unaware of how effectively Prop 1B funds are spent. This 'no data, no accountability' story is repeated across the country.

expect and how the system actually performs". Evidently, (1) and (3) coincide with FHWA's two definitions, whereas (2) is a quantitative gloss on definition (1) via the speed-flow relationship.

FHWA and OECD both agree that congestion is measured by performance reduction. They also claim that performance reduction is caused by excess demand. We call this the 'excess demand' hypothesis. We propose 'inefficient management' as an additional hypothesis. Empirical evidence suggests inefficient management is pervasive. The cure for congestion will depend on its cause: inefficient management should be replaced by better traffic control, and excess demand should be reduced by demand management.[4] We first consider freeway and then arterial congestion.

2.1 Freeway Congestion

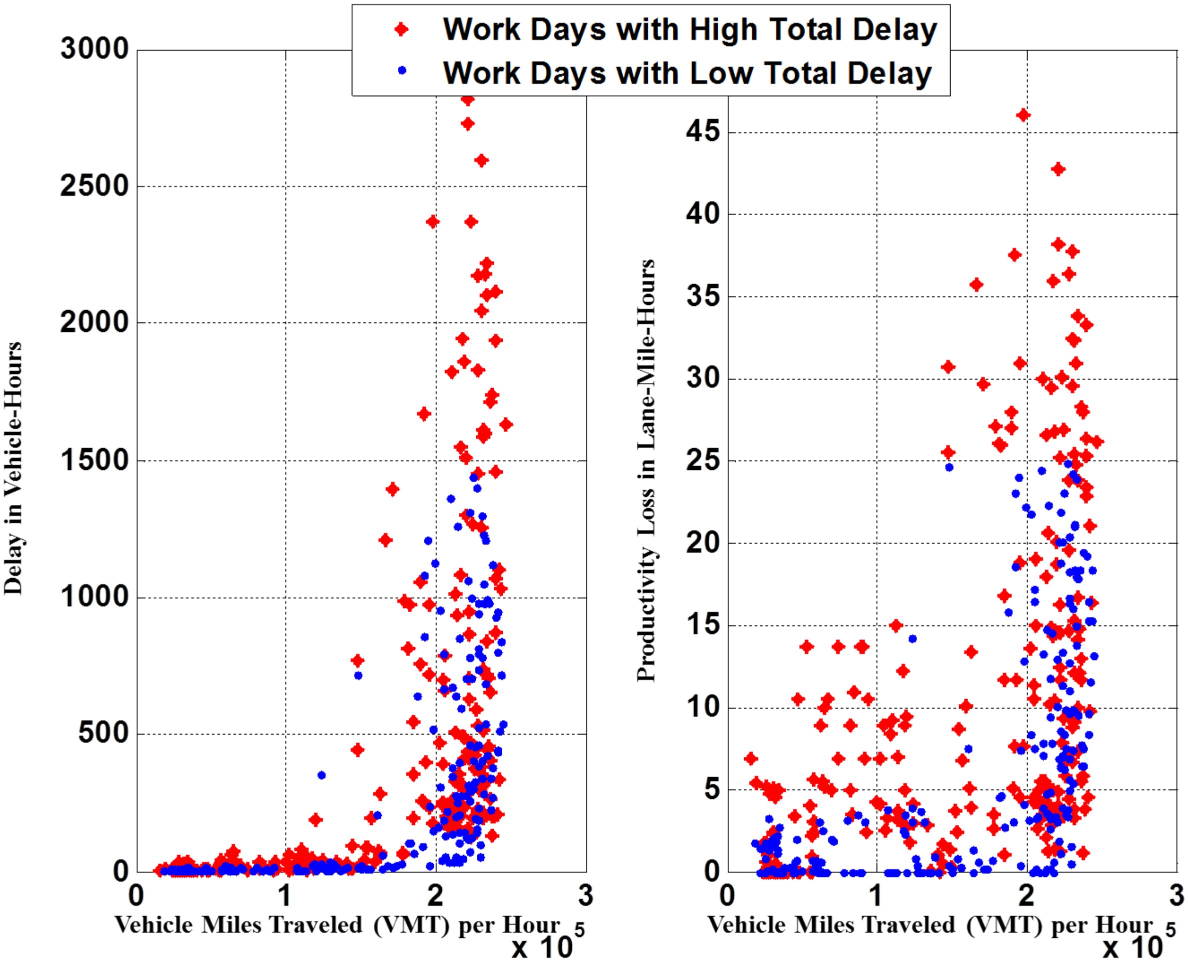

Figure 2: I-880S: delay vs. Vehicle Miles Traveled (VMT) (left) and productivity loss vs.VMT (right) for each hour on workdays in November-December 2013. Source: PeMS [5].

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[4] Excess demand causes congestion as a negative externality. Inefficient management leads to X-inefficiency [42], which is the failure to achieve technical efficiency and can occur from the lack of competitive pressure. Roadway operators are monopolists, with uninformed customer-users.

Consider Figure 2 (left). It is a scatter plot of vehicle-miles traveled (VMT) on the x-axis vs. delay in vehicle-hours on the y-axis, calculated for a nominal speed of 45 mph. Each point represents one hour of each workday in November and December of 2013 for vehicles traveling the 45 miles of Interstate 880 South in San Francisco Bay Area, from Oakland to Santa Clara. Each day is classified as a good day, and their hourly data are in blue, or as a bad day with red data points. We take VMT as a measure of hourly *demand*. Observe that as the demand varies by 25% between 200,000 and 250,000 vehicle-miles the delay varies by 1500% between 200 and 3,000 vehicle-hours. More importantly, for the *same* value of demand the delay at different hours or days varies drastically. So it is not possible to support an excess-demand hypothesis either in the form: if VMT exceeds capacity C, delay will exceed D, or in the form of a speed-flow relationship.[5]

By contrast, the 'inefficient management' hypothesis asserts that the capacity is a stable number (absent incidents or adverse weather) and that if the freeway is well managed, it will keep vehicles moving at free flow speeds. Caltrans measures the efficiency loss from poor management as lane-mile-hours of 'productivity loss'. The notion is this. The capacity of a homogeneous section of freeway is estimated from measurements as the maximum number of vehicles per hour per lane (VPHPL) that traverse this section at free flow speeds. For California freeways, typical values are 2,000 VPHPL at 45 mph. Suppose that in a 4-lane 1-mile long section during a certain hour, the flow reduces to 1,500 VPHPL and the speed to 30 mph. So the per-lane 'output' of this freeway section during that hour is 1500×30 vehicle-miles compared with a capacity output of 2000×45, for a loss in potential output of $(2000 \times 45 - 1500 \times 30)/(2000 \times 45) = 50\%$. As this section has 4 lanes, the productivity loss during that hour is $0.5 \times 4 = 2$ lane-mile-hours. Figure 2 (right) is a scatter plot of the hourly productivity loss vs. demand for the same freeway and times as in the left plot. Note that a loss of 40 lane-mile-hours means that a 4-lane, 10-mile section of the freeway is effectively shut down for one hour, which represents a very unproductive use of the capital embodied in the freeway, not to mention the loss in travel time and fuel.[6]

Figure 2 shows that a nearly identical hourly demand profile can be accompanied by a very low or high delay, which violates the 'excess demand' hypothesis. The poor management hypothesis offers a different explanation: since this freeway uses time-of-day ramp metering, which does not respond to fluctuations in traffic, the delay is a random outcome, and most days would be 'bad'.[7] However, a good traffic-responsive ramp-metering strategy would prevent congestion, so all days would be 'good'. We now attempt to demonstrate this.

One effective ramp metering algorithm is ALINEA [55]. It decreases the on-ramp flow rate when the freeway traffic volume at the on-ramp approaches capacity, and increases the rate when the freeway traffic becomes less dense. It is generally a good idea to use ramp metering in combination with ramp queue control. Queue control estimates the number of vehicles queued at the on-ramp, and once the ramp storage limit is reached, it increases the flow rate from the on-ramp, overriding rates set by the metering algorithm, to prevent the ramp queue from spilling back into the city street.

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[5] One could argue that capacity is not a stable number; rather, as the FHWA article states, it "varies constantly, being frequently reduced by incidents (e.g. crashes and disabled vehicles), work zones, adverse weather, and other causes." There is a danger that with a too-elastic notion of capacity, the excess demand hypothesis reduces to a tautology.

[6] The 3-mile double-decker section of I-880 was replaced following the 1989 earthquake at a cost in excess of $1.2B. So the monetary equivalent of the productivity loss is not small.

[7] The reason is that once congestion starts, in the absence of an appropriate ramp-metering response, congestion will persist and propagate upstream. In Figure 2 on the bad day, the congestion during the mid-day lull was not cleared and spilled into the afternoon peak causing large delays. An examination of the delay on I-880S for one year, reveals that most days are 'bad'.

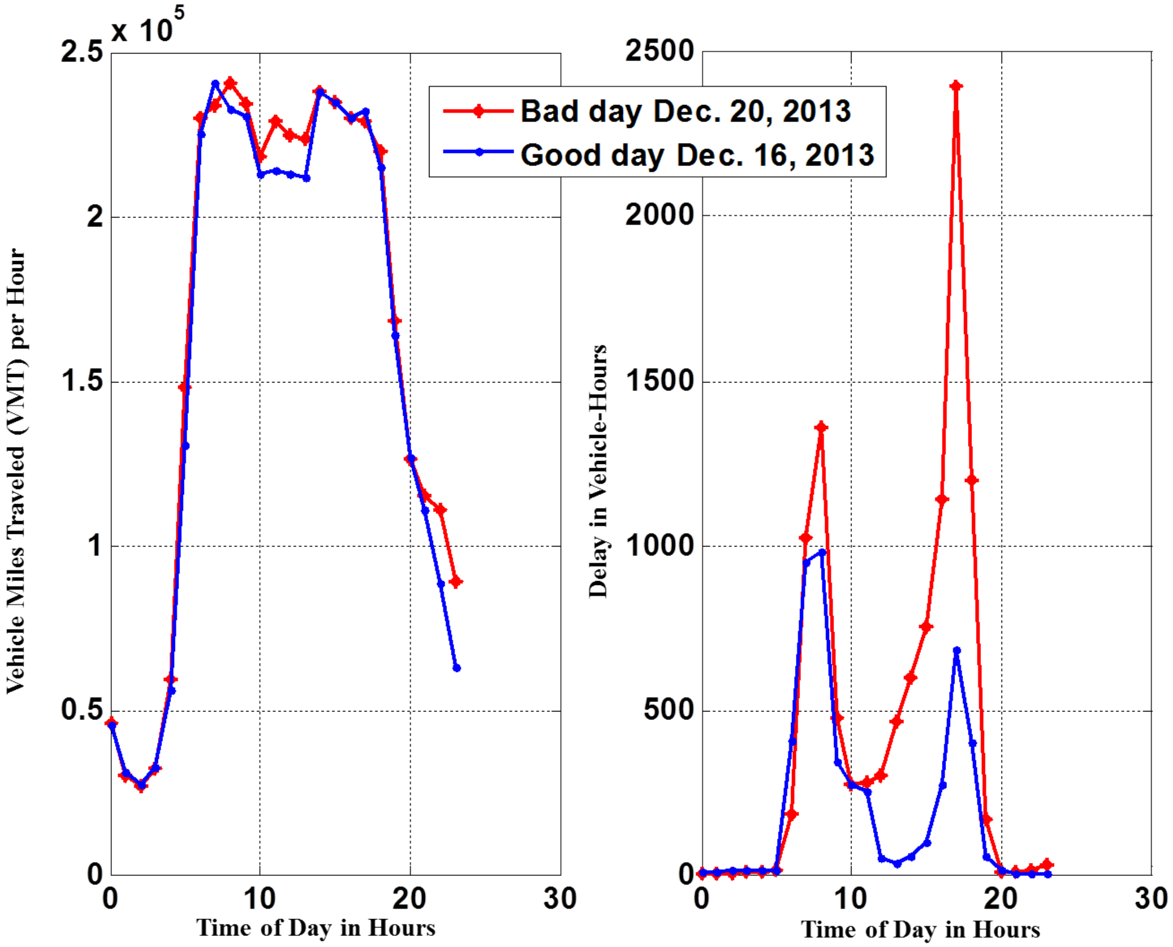
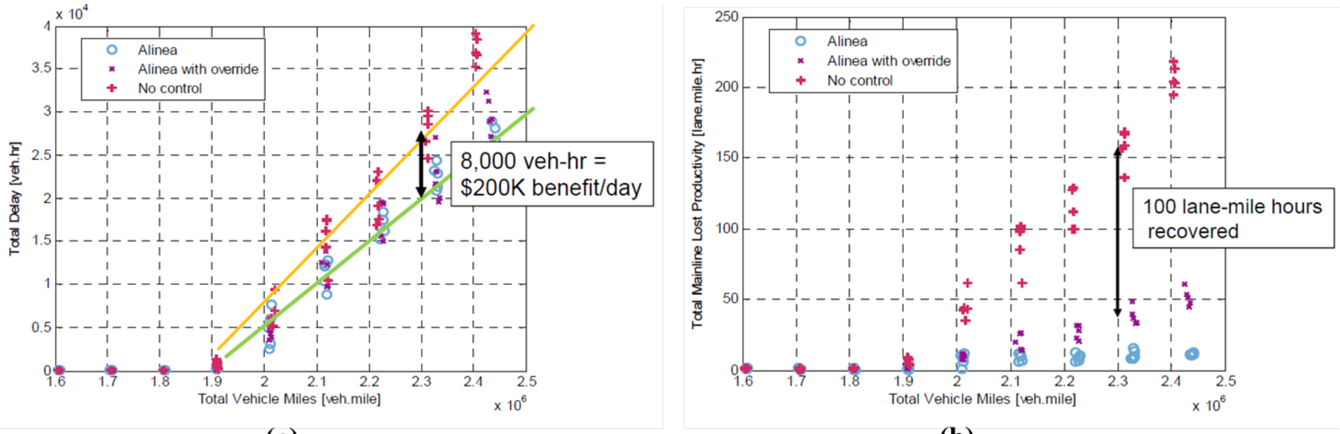


Figure 3: Two days with similar demand on I-880S: high delay on December 20, 2013 vs. low delay on December 16, 2013. Source: PeMS [5].

We recall the results of a 2010 simulation study [64] on the benefits of ramp metering on the 23-mile section of Interstate 80 East from the San Francisco Bay Bridge to the Carquinez Bridge [69]. The study uses a calibrated cell transmission model (CTM) [48]. Bounded uncertainty is introduced in the freeway link capacities and on-ramp demands. A hundred datasets within the given uncertainty bounds were generated for the simulation input. Three simulations were run with each input dataset: (1) no ramp control – the base case, as this freeway has no ramp metering; (2) ALINEA ramp metering; and (3) ALINEA combined with ramp queue control. The results comparing these three management strategies are presented in Figure 4. Each scatter point summarizes one experiment for one day. The x-axis is the demand in vehicle-miles (same as VMT), the y-axis is the total delay (relative to 60 mph) *including* the delay on the ramps in the left plot, and the freeway productivity loss in the right plot.

Ramp metering reduces the total delay by more than 8000 vehicle-hours (for an imputed daily benefit of \$200K) and recovers more than 100 lane-mile-hours of freeway productivity – equivalent to one of four lanes of the 23-mile freeway for one peak hour. With good ramp-metering the freeway productivity loss increases from 10 to 45 lane-mile-hours as the demand increases from 2



(a) **(b)**

Figure 4: Results of stochastic simulations for for no control, ALINEA ramp metering and ALINEA with queue override strategies: (a) comparison of total network delay including ramps; (b) comparison of the mainline productivity loss. Source: [69].

to 2.5 M vehicle-miles. In the base case, the loss increases from 10 to 200 lane-mile-hours. The productivity loss is kept low because good ramp metering keeps vehicles moving at nearly free flow speeds and close to capacity. The cost of good management is that vehicles must wait on the ramps: indeed since vehicles on the freeway are moving at 60 mph, nearly all of the delay occurs on the ramps. This last observation could be used to reconcile the 'excess demand' and 'poor management' hypotheses. Good management eliminates freeway congestion and the residual delay occurs on the ramps. This residual delay is similar in nature to the delay analyzed in an idealized setting in [72]. From Figure 4(a) if we take demand as 2.35M vehicle-miles, the base case shows a total delay of 30,000 vehicle-hours, whereas the 'ALINEA with queue override' strategy imposes a total delay of 20,000 vehicle-hours, so one could attribute 10,000 vehicle-hours of delay to inefficiency and 20,000 vehicle-hours to excess demand.

In summary, freeway congestion delay has two parts: delay on the freeway from lower than free flow speeds at less than capacity flows, caused by inefficiency, and a residual delay, confined to on-ramps in a well-managed freeway, which may be attributed to excess demand. A good traffic measurement system is essential to measure the delay, diagnose its causes, and design and implement effective management strategies. Delay from inefficiency may be eliminated by good management; reduction of delay from excess demand may require demand management policies, considered later.

2.2 Arterial Congestion

According to TTI's Figure 1(b) 60% of delay occurs on urban streets. An estimated 2.3M crashes occurred at intersections in 2008, accounting for 40 percent of 5.8M crashes, resulting in 7,421 fatalities (including 4,092 pedestrians) and 733,000 crashes with one or more injuries [50]. These mobility and safety costs will increase as cities try to provide transportation choices to all citizens, whether it's by walking, bicycling, transit, or driving. Unless carefully managed, the dedication of more road surface to pedestrians and cyclists will cause greater congestion and increase pedestrian-vehicle conflicts and accidents. Unfortunately, intersections are generally very badly managed.

More than 90% of the 300,000 signalized intersections in the US are regulated by pre-timed controllers, with their associated timing plans. The timing plans determine how well or poorly the intersections operate. The 2012 national traffic signal assessment conducted by the National Transportation Operations Coalition (NTOC) is based on 241 respondents, accounting for 39 percent of all traffic signals. Its report card gives the following grades [49]:

- signal operation at individual intersections — C;
- signal operation in coordinated systems — D;
- signal timing practices — C-; and
- traffic monitoring and data collection — F.

One reason for the poor NTOC grade is that "only 60 percent of the respondents indicated that they re-timed signals at intervals of 5 years or less" [23].

Like time-of-day ramp metering, a pre-timed controller at an intersection does not respond to a change in traffic. Its timing plan is determined as follows. Traffic volumes and turn movement counts at the intersection are manually measured over two or three days. The measurements are input to a software package like Synchro or Transyt which outputs 'optimal' timing plans. Traffic is measured once every three to five *years*, and between successive measurements, the intersection control scheme is unchanged. Since the traffic patterns change constantly, the intersection becomes inefficient, increasing delay and compromising safety. Thus the default hypothesis for virtually all intersections must be that they are inefficiently operated.[8] Poorly-timed signals can cause great delay. Suppose, the volume of traffic in one direction along an arterial has increased to 1,000 vehicles per hour, but the pre-timed signal is set for a flow of 900, leading to an excess of 100 vehicles per hour. With 20 feet per vehicle spacing, a two-lane link, 260 feet in length (typical length of a city block), will become saturated in 16 minutes, causing traffic to spill back, and flows to drop further. Upstream links will become saturated, even though their signals are well-timed. The condition will persist until demand drops, which may occur because frustrated drivers take alternate routes.

In an urban mesh street network, there are many origins and destinations, so it is difficult to specify 'demand' or 'capacity'. Moreover, since drivers will take alternative routes when confronted with saturated links, it seems impossible to empirically specify and test the excess demand hypothesis. Recent attempts at formulating a 'macroscopic fundamental diagram' that models a 'homogeneous' urban area (e.g. 'downtown') as a single link [30], can lead to a notion of excess demand, prompting proposals for traffic control similar to ramp metering [24] and for demand management via a congestion charge. However, since it is virtually certain that the intersections within the congestion charge area are *not* efficiently managed, these proposals will not improve efficiency.

3 Traffic Control and Demand Management

Road traffic is controlled by intersection signals, freeway on-ramp metering signals, and variable message signs giving information about diversions, warnings of congestion ahead, and estimates of

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[8] Traffic-responsive and adaptive signals achieve large benefits: 13%-50% reduction in travel time and 8%-38% savings in fuel [43]; yet fewer than 10% of intersections use adaptive signals.

travel times along a few routes. The signal settings are determined by a closed-loop feedback system comprising a sensing system that measures traffic, algorithms that process the measurements to estimate the traffic state, and procedures for calculating the signal settings based on the state estimate. The goal of traffic control is to maintain efficient operations. Traffic is also managed by restrictions on demand, e.g. high-occupancy vehicle (HOV) lanes, or by pricing, e.g. tolled lanes. The purpose of demand management is to shape the pattern of demand to match an efficiently (or inefficiently) controlled supply of transportation service. It may help to think of traffic control as affecting the *supply* while demand management acts upon the *demand* for transport services. Collectively, these traffic control and demand management systems are called Intelligent Transportation Systems (ITS).

3.1 Traffic Control

Although in use for 20 years, ITS remains an aspirational term.[9] Compared with the volume and variety of ITS R&D activity, the impact of ITS on the ground is undetectable, outside a handful of agencies. As noted earlier, 90 percent of intersections and ramps do not have or use measurements. These are open-loop systems that produce a time-driven actuation signal: a pre-timed intersection control implements a periodic pattern of phase actuations; and a time-of-day ramp controller permits vehicles to enter the freeway at a pre-determined time-dependent rate. The parameters of the pre-timed intersection and time-of-day ramp controllers are based on manual traffic measurements carried out years before. We expect these open-loop systems to be inefficient, so that on the rare occasions an open-loop system does get re-timed, there may be large benefits.[10] A few agencies have an experienced traffic engineer who periodically (say once a year) observes the traffic, locates problem intersections, and re-tunes the timing plans to improve performance.

The first ITS control systems can be described as systems that follow the 'measurement - state estimation - signal actuation' closed loop. There is a variety of such systems depending on how each of these three activities is carried out.

Traffic Measurement The most ubiquitous and most unreliable traffic measurement systems are based on inductive loop sensors; recent systems use video, radar or wireless sensors that are much more reliable. All these sensors detect the passage of a vehicle at a specific location in a specific lane. Typically they report volume, occupancy and speed (VOS) measurements at that location. The performance of the control system is limited by the spatial resolution of the VOS sensors: are there sensors at mid-block as well as at the intersection stop bar, are there sensors in every freeway lane every one-third mile, etc.? Even though the cost of additional sensors is small compared with the fixed cost for communication, computing and maintenance of a sensor system, most agencies skimp on the number of installed sensors, so they have a low-resolution system that cannot support any advanced signal control algorithms.

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[9] The FY 1991 House Transportation Appropriations report states: "The Committee is . . . concerned about the apparent lack of a nationwide public/private coordinating mechanism to guide the complex research and development activities anticipated in the IVHS [Intelligent Vehicle Highway Systems] area." In response, IVHS America was formed as a partnership of the public, private and academic sectors involved in IVHS. In 1994 IVHS was renamed ITS (Intelligent Transportation Systems), and IVHS America became ITS America.

[10] In 2012, Lee County in Florida re-timed 50 intersections at a consultancy cost of $357,400 and estimated annual benefits that include $15.3M in time saved, $2M in fuel cost reductions and 19% reduction in emissions valued at $.12M, a benefit-cost ratio of 49 [35]. An earlier survey of signal re-timing finds a benefit-cost ratio of 40 [63].

Electronic tag, licence plate and bluetooth readers record the identity of individual vehicles at specific locations, from which one can estimate their speed. For various reasons, these sensors have been deployed on a limited basis. Much more widely available are records of GPS traces from applications on user cell phones and vehicle navigation systems. These records are forwarded to companies like Apple, Google, INRIX, Nokia/NAVTEQ and TomTom, which provide maps with roads colored red, yellow, green to indicate speed or gray to indicate 'no data'. Fleets of taxis or delivery trucks may also provide such data. Since the cost of collecting and transmitting these data is borne by the cellphone owner, and since there are billions of such cellphones in the world, transportation agency chiefs in states and local agencies like to believe that a traffic data nirvana is close at hand, obviating the need for infrastructure-based sensing systems.[11] Transportation engineers do not believe their chiefs, because they understand that the most basic measurements needed for traffic control are traffic volume and occupancy, which cannot be obtained from GPS traces for the simple reason that one does not know the fraction of all vehicles traveling in a particular direction at a particular location (say northbound at an intersection or near an on-ramp) that is providing its GPS data; without this fraction one cannot correctly inflate the GPS count to estimate total vehicle count or occupancy. The TTI estimates use GPS-based speeds and vehicle counts from infrastructure sensors.

GPS traces can give a vehicle's travel time along its route. Traffic agencies can use aggregated historical travel times to locate congestion along freeways that have no sensors. Travelers can use online maps with colored roads to guide their trip start time or to select a route. However, the quality and utility of travel time information to drivers has so far proved insufficient to sustain a business. Further Apple, Google, TomTom, et al, provide this information for free in exchange for getting user location information. Potentially of greater value in understanding travel demand is the possibility of online activity surveys that combine location traces with user feedback [8]. Of couse, Facebook et al, with their much wider nets of data collection, produce and exploit more detailed estimates of user activity.

Traffic state estimation Feedback control algorithms use estimates of the traffic state to determine the signal settings. These are estimates of the state of a dynamic model of traffic flow. For freeways, engineers use first-order (with density as state) or a second-order (density and speed as state) model. The models can be calibrated if sensor data are available, and standard statistical techniques can be used to process measurements to estimate the traffic state [20, 48, 57]. If a statistical forecast of future on-ramp demand is available, it can be used to predict the future state. If one can only provide a bound on future demand, that, too, can be used to bound the future state [39].

For signalized arterials, the question of state estimation is less well-defined. The cell transmission model (CTM) commonly used for freeways formally can be used for signalized streets [44], but there are difficulties with calibrating such a model. More common is a point-queue model, similar to those used in communication networks, e.g. [21, 53]. In such a model vehicles form a 'vertical' queue at the stop bar from which they are discharged at a saturation rate, travel over a link in a fixed time and then join the queue at the next intersection. Such a model requires only link travel times, saturation flow rates and demand (volume and turn movement counts) that can be empirically measured. For control of a corridor that includes freeways and adjacent signalized streets, one could combine a CTM model for the freeway with a point-queue model for the streets.

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[11] An early example is the 2004 discussion paper prepared for the TRB Regional Transportation System Management and Operations Committee. It starts with the prediction: "within 1 to 3 years real-time, comprehensive travel time and other traffic flow data will be available from the private sector for all major roadways [14]." Such optimistic forecasts are recurrent, e.g. [77, 38].

Signal actuation For freeways the most important control variable is the ramp-metering rate. There are many algorithms that determine this rate based on the freeway state (vehicle density) and, possibly, ramp queue. We have already mentioned ALINEA [55]. A coordinated version of ALINEA called HERO is designed to control a collection of consecutive ramps and successfully used in the control of the Monash freeway in Melboune [56]. Numerous simulation-based studies, like that in Figure 4, demonstrate that intelligent ramp-metering is a sound means to keep freeways operating efficiently. However, agencies are unwilling to invest in the sensing infrastructure needed to implement these ramp-metering algorithms. The benefits are enormous: according to [56], speeds increased by 59% and productivity by 155%. The cost is comparatively trivial: we estimate that sensing the queue on one on-ramp and VOS at (say) two nearby freeway locations would cost $100K. The 26 on-ramps on I-80E freeway could be instrumented for $2.6M, for a 10-year lifetime. According to the $200K daily benefit estimate shown in Figure 4, the cost would be recovered within 13 days! This is not unbelievable: in the Monash freeway, engineers first piloted the ramp metering strategy on a section with 6 consecutive ramps at a cost of AU$1M; according to their report "results have exceeded expectations in reducing delays, improving reliability and increasing traffic throughput. The economic payback period of the pilot project was 11 days." But transportation agencies do not undertake such obvious investments.[12]

A rich literature on the feedback control of signalized intersections is reviewed in [46, 54, 52, 76, 70]. Unfortunately, local and state agencies refuse to invest in the traffic measurement systems these feedback schemes require. According to [23] these schemes can only be implemented by "three dozen or so agencies in the United States capable of routinely collecting and archiving second-by-second advanced detector volumes and occupancies for extended periods of time (on the order of one full year)."

Advanced control While local and state transportation agencies have refused to implement feedback control schemes at intersections or at ramps, Research and Innovative Technology Administration (RITA) and FHWA continue to fund research and demonstration of new technologies, including Active Transportation and Demand Management (ATDM), Integrated Corridor Management (ICM), and Connected Vehicles, as well as demand management projects.

ATDM and ICM ATDM postulates substantial flow improvements as a result of close road network monitoring and proactive application of both direct traffic control and pricing schemes. A related concept, ICM, seeks further gains from interconnecting different transportation subsystems, say a freeway, a parallel transit corridor, and adjacent urban streets. In 2008 United States Department of Transportation (USDOT) selected three "pioneer sites" (Dallas, TX; Minneapolis, MN; and San Diego, CA) to conduct analysis modeling and simulation of their ICM concepts, and later chose two sites (Dallas, TX and San Diego, CA) to demonstrate their ICM systems. These demonstrations are expected to occur in 2014. ICM systems are supposed to test the maturing ITS technologies, determine the types of data needed for effective ATDM application, establish institutional framework for cooperation between multiple agencies, and define performance measures to be used for evaluating ICM efficiency.

Autonomous vehicles Autonomous vehicle (AV) technology was developed over the past four decades. The formation of the National Automated Highway System Consortium (NAHSC) in

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[12] It is disappointing to note that $85M in Prop 1B is being spent for congestion relief on the I80 freeway between Bay and Carqjuinez bridges. More than the amount that would have provided for instrumentation has been spent on congestion relief "planning" studies that lack empirical foundation, e.g. [22].

1994 boosted related R&D, and the Automated Highway System (AHS) project [15] successfully demonstrated a high-speed, tightly-spaced platoon of driverless vehicles in July 1997 on the I-15 freeway in San Diego [28]. Some may also recall the history of AHS development in Japan [65]. AV technology development received a further impetus through the DARPA Grand Challenge [17] in 2004-2007. It led to the Google driverless car [32] in 2010, which captivated the press [4], vehicle manufacturers, states seeking to welcome AVs, as well as academics.

Here are some forward-looking industry announcements. By 2016 Tesla expects to develop technology that permits 90% of the distance to be driven autonomously [73]; Mobileye expects to release a fully autonomous car technology [18]. By 2018 Google expects to release its autonomous car technology [51]. Audi, BMW, Daimler, Nissan and Volvo, all plan to start selling autonomous cars by 2020 [36, 25, 59, 74, 34]. In the hope of becoming the home to the future 'autonomous car' industry, as of 2013, Nevada, Florida and California have passed laws permitting their Departments of Motor Vehicles to license testing of such vehicles. Universities have joined the race. One of them has publicized research that will do away with intersection control, dramatically reduce delay and fuel consumption, and improve safety [66]: instead of waiting for the signal, vehicles negotiate their passage through intersection with one another.[13]

Connected vehicles The USDOT through its Research and Innovative Technology Administration (RITA) has promoted R&D activity on connected vehicles. This concept has gone through many name changes and refinements from vehicle-to-infrastructure (V2I), to vehicle-to-vehicle (V2V), to Intellidrive. In bureaucratese, "The development and deployment of a fully connected transportation system that makes the most of multi-modal, transformational applications requires a robust, underlying technological platform." A more concrete goal is V2V and V2I communications for safety, e.g. warnings of emergency braking or a vehicle in a blind spot during lane changes.[14]

The auto industry may be more interested in a Deloitte survey of 1,000 respondents, which found "84% indicated emailing or texting and 24% indicated the use of smartphone applications as the features they expect in a connected vehicle; many ranked streaming entertainment content as most desirable ..." [19]. The popularity of the Waze social network for driving community supports these findings. Of course, such connected driving will distract drivers and increase accidents.

3.2 Demand Management

Excess demand causes congestion. One way to reduce demand is to encourage car pools through an exclusive HOV or high-occupancy vehicle lane.[15] With fewer vehicles, a trip in the HOV lane will take less time than a trip in the general purpose (GP) lanes; HOV advocates say the time savings will encourage the formation of car pools and reduce demand.

Congestion is a negative externality: the average trip time is smaller than the marginal total time of everyone making this trip. A 'congestion fee' equal to the difference in the two costs will 'internalize' the externality and lead to demand that accurately reflects cost. The introduction of HOV lanes

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[13] This research may have been anticipated in 1991 by a Dutch engineer who used the concept of "shared space" to advocate improving traffic efficiency by eliminating traffic signals and have each driver make their way through the contested intersection by direct negotiation with others [75].

[14] RITA is seeking to mandate direct short range communication (DSRC) systems on all vehicles.

[15] Typical minimum vehicle occupancy level for HOV lanes in the U.S. is 2 (2+HOV) or sometimes 3 (3+HOV).

in the U.S. progressed slowly during 1970's and early 1980's. Major growth occurred from the mid 1980's to the end of 1990's. Intended to reward people traveling in groups with shorter travel time, HOV lanes were criticized for being underutilized, thereby worsening the overall traffic congestion on highways. This criticism led to the concept of High Occupancy Tolled (HOT) lanes. The first HOT facility, SR91 Express, was launched in Orange County, California, in 1995. Since then, over 40 similar projects were initiated across the U.S. with tolls ranging from 25 cents to $14 [67]. While HOV lanes are not favored as they once were, HOT lanes are still in fashion, especially because they offer the prospect of raking in revenues. In California, HOV and HOT lanes have not delivered what planners promised.

HOV lanes California's 1,326-mile HOV system (accounting for 40% of the nation's managed lanes) was intended to increase the people-moving capacity of the freeway system through carpooling; reduce overall congestion; provide travel time savings to HOV users; increase system efficiency by allowing HOVs to bypass congestion; and decrease emissions [41]. The 2+HOV system has not met these goals. An extensive statistical study of California's HOV system [40] can be summarized as follows.

1. HOV lanes are underutilized: 81% of HOV detectors measure flows below 1,400 vehicles per hour per lane (vphpl) during the PM peak hour.
2. Many HOV lanes experience degraded operations: 18% of all HOV miles during the AM peak hour and 32% during the PM peak hour have speeds below 45 mph for more than 10 percent of weekdays.[16]
3. HOV lanes suffer a 20% capacity penalty, achieving a maximum flow of 1,600 vphpl at 45 mph vs. maximum flow above 2,000 vphpl at 60 mph in GP lanes.
4. HOV lanes offer small travel time savings. The mean savings over a random 10-mile route on an HOV lane vs. the adjacent GP lane is 1.7 minutes and the median is 0.7 minutes; however, HOV travel times are more reliable.
5. Travel time savings do not provide a statistically significant carpooling incentive: carpooling is declining and overwhelmingly only serves 'fampools'.

Accordingly, goals for the Prop 1B-funded expansion of the HOV system have been trimmed to improving travel times and reducing delay; encouraging carpooling and decreasing emissions have been dropped [7, p.2]. But the reduced goals cannot be met either: as [40] shows, a system with one HOV lane and three GP lanes carries the same number of persons per hour as a system with four GP lanes; and HOV lanes reduce overall congestion slightly only when the general purpose lanes are allowed to become congested.

HOT lanes (The term of art now is 'express lanes', although 'managed lanes' and 'value pricing' are also employed.) Already at the 11th International Conference on HOV Systems held in 2002, speakers were troubled by underutilization and congestion, evidenced by peak period volumes below 800 vehicles per hour and, at the same time, speed below 45 mph in many HOV facilities. Enthusiastic proponents pressed for strong marketing of the HOV program implying the need for

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[16] An HOV facility is "degraded" if speed drops below 45 mph for 10% of the time during a six-month period [68]. The situation has worsened: Caltrans reported to FHWA that 49% or 656 lane-miles were degraded in 2011 [6].

public for re-education [26, p.28]. More sophisticated voices called for abandoning the HOV slogan and replacing it by a new one: *managed lanes* — a catchall category denoting priority access for express trips, buses, commercial vehicles, zero emission vehicles, high energy efficiency vehicles, tolled vehicles and HOVs. 2+HOVs gained a new lease on life as 2+HOTs.

Consider the case of the 14-mile Interstate 680 South express lane. A 2006 report on a "Regional HOT lane network study" to the Metropolitan Transportation Commission (MTC) Advisory Council, claimed that converting HOV lanes to HOT lanes would generate \$2B to \$4B between 2015 and 2045, and I-680 was one corridor with the highest 30-year net revenue potential of \$575M to \$745M, corresponding to a revenue/cost ratio rising from 4.7 in 2015 to a whopping 13.8 in 2030, with cost defined as amortized capital cost plus O&M cost [58]. The consultant forecast an average revenue per mile of \$1.7M or \$24M for the 14 mile facility (in 2005 dollars) between 2015 and 2030. The consultant estimated the O&M expenses (not including pavement maintenance) of the express lane at \$1M per year.

The I-680 express lane has been operating for three years since September 2010. We first look at its finances from the annual reports for FY2010-11 and FY2011-12 [12, 13]. The two reports differ over the project cost: the earlier report states the express lane cost \$37M, the later report puts it at \$41M.[17] The toll revenue for Sept 2010-June 2011 was \$629K and for June 2011-June 2012 it was \$1.1M. The annual reports do not give O&M expenses, but admit that "revenues do not exceed operating costs, and the express lane is subsidized by grant funding." It will be several years before the express lane will meet its O&M costs. It is unlikely that it will ever have revenues equaling 4.7 times cost as was projected for 2015. Nevertheless, the express lane authority expects to use surplus revenues for transit and to extend the express lane to I-680N. And MTC plans on adding 150 miles of HOT lanes (plus 120 miles for lane widening for the HOT lanes) [3].

The financial infeasibility of the express lane was apparent in 2008 [71]. Although MTC in 2006 and the express lane authority's FY2010-11 report declared I-680 to be at "the top of the Bay Area's list of most congested commute corridors", in fact there is very little congestion. And whatever little congestion there is, is the result of inefficient management. The lack of congestion is evident from Table 1 comparing the average speed over the 14-mile trip for the HOV lane vs. the second lane during April 1-July 1, 2008, before the express lane. Table 1 reveals that the HOV lane was extremely underutilized. Only during 8-9AM did driving on the HOV lane provide a perceptible advantage 64.7 vs. 55.2 mph or a travel time of 13.0 vs. 15.2 min; during 5-6PM the advantage was 71.9 vs. 66.2 mph or 11.7 vs. 12.7 min.

	5-6AM	6-7AM	7-8AM	8-9AM	3-4PM	4-5PM	5-6PM	6-7PM
HOV	73.4	72.0	68. 3	64.7	74.0	73.3	71.9	75.6
Lane 2	72.4	70.7	65.6	55.2	72.5	71.3	66. 2	73.8

Table 1: Speed on HOV vs. lane 2 on I-680S, April 1-July 1, 2008, based on MTC data. Source: PeMS (2007) [5].

Five years later in 2013, I-680 traffic remains unchanged. Table 2 gives the average speed and hourly flow in the express lane (Ln 1) and the adjoining GP lane (Ln 2) during the AM peak period

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[17] The cost could have been underestimated, for according to [12] the express lane was part of a larger \$195M project that included "new two-foot buffer, separating the lane from the general-purpose lanes, installing electronic toll-collection equipment, re-paving the entire roadway, and adding soundwalls". Some of these improvements are surely for the express lane.

Date	Ln 1 mph	Ln 1 vph	Ln 2 mph	Ln 2 vph
Dec 3	75	1168	70	2060
Dec 4	76	1160	72	2033
Dec 5	79	1198	65	1957
Dec 6	77	877	73	1943

Table 2: Average speed and hourly flow in express lane vs. lane 2 at Sheridan Ave, 6-10 AM, December 3-6, 2013. Source: PeMS (2013) [5].

6-10AM, Dec 3-6, 2013. The measurements are taken by a Caltrans vehicle detector station (VDS 403334) located at the Sheridan lane crossing, about mid-way along the express lane. The relative speeds are similar to those five years earlier shown in Table 1. There is no congestion. In the GP lane the flow is 2000 vph (close to capacity) at 70 mph; the flow in the HOT lane is below 1200 vph, or 40 percent below capacity. In the PM peak 4-7PM, HOT lane hourly flow averaged below 300 vph (80% below capacity!), lane 2 averaged above 1500 vph, with speed in both lanes above 70 mph.

According to [13], in the AM peak only 300 of the 1200 hourly vehicles (including 2+HOV vehicles) paid a toll, which averaged \$3; in the PM peak only 75 of the 300 hourly vehicles paid a toll averaging \$0.50. Clearly, the toll is not efficient: with 40% (85%) excess capacity in the AM (PM) peak, the toll should be much lower, increasing the number of toll-paying vehicles in the express lanes but lowering revenues, reducing the flow on the GP lane, while maintaining 65 mph across all lanes. Thus, the express lane's pricing appears to be monopolistic. This illustrates California's HOT lane dilemma: the only way to increase revenues is to raise prices well above what is dictated by efficiency considerations. It also indicates the incentive to mismanage the GP lanes: the slower the GP lanes, the higher the express lane toll. One should not be surprised that sensing and ramp-metering infrastructure on I-680S have not been installed. It's impossible for the public (or the authorities) to know how poorly managed the system is.

In its Bay Area Plan [3] MTC (the Bay Area MPO) expects to re-time signals at 500 intersections each year and add 150 miles of HOT lanes by 2035. With its 7M population, the Bay Area likely has 7,000 signals, so it will take 14 years (!) to re-time each signal. This derisory funding of re-timing means that Bay Area city streets are condemned to growing congestion. The HOT lanes are expected (1) to use "excess capacity in the existing HOV system to reduce travel time for all travelers," and (2) to provide "toll revenue to close gaps within the HOV lane system and to increase travel-time savings for carpools and buses." The I-680S express lane example (which is replicated in I-394 in Minneapolis and I-15 in San Diego [71]) suggests these goals will not be achieved: the HOT lanes will be underutilized, there will be no surplus revenue to fund transit, and the authority will raise tolls to reduce deficits by mismanaging the GP lanes and making both GP and HOT lane users worse off. One can only speculate why in the face of all evidence, MTC continues to be so bearish on traffic control and bullish on HOT lanes. First, transportation planners do not recognize inefficiency as a cause of congestion and feedback control as a means to relieve it. Second, they believe congestion is caused by excess demand, which must be reduced by increasing the cost of driving through tolls. Third, UDOT, also in thrall to the excess demand hypothesis, makes HOV in most cases "the only alternative, in meeting federal air quality conformity standards for capacity-increasing improvement project in metropolitan areas," according to Caltrans. This 'no HOV-no federal subsidy' policy guarantees the spread of the HOV system.

Area tolls Area tolls are fees paid by drivers to enter a restricted area, usually within a city center.

First implemented in Singapore in 1975, this pricing scheme was adopted in Rome in 2001, London in 2003, Stockholm in 2006, Milan in 2008 and Gothenburg in 2013. Singapore and Stockholm charge a congestion fee every time a driver enters the area, while London charges a daily fee regardless of how many times the vehicle enters the area. Stockholm has put a cap on the maximum daily toll, while in Singapore the charge is based on a pay-as-you-use principle, and rates are set based on traffic conditions at the pricing points, and reviewed on a quarterly basis. Restricted areas have 'gates', through which cars enter and exit. Electronic tags are registered at the gate and license plate readers are used for enforcement. With the exception of Rome, cities report traffic volume reductions after the implementation of area tolls. At the same time, all cities report public controversy before and after implementation, making area tolls a sensitive political issue. As a result of negative public reaction, area tolls were rejected in New York, San Francisco, Hong Kong, Edinburgh, Birmingham, Coventry and Manchester. For a recent survey, see [2].

A cost-benefit analysis of a 'Western Extension' of the London Congestion Charging Scheme (LCCS) is carried out in [60]. The highest estimates of the benefit-cost ratio, which assumes the greatest possible environmental and accident benefits, is 0.9. So the scheme produces net *negative* benefits, i.e., car users pay a higher congestion charge than the gain to bus users from reduced congestion. Part of the reason is the very high cost of implementing the scheme with its 174 entry and exit points, administration and enforcement.

In the Bay Area MTC is planning a \$150M subsidy to a congestion pricing scheme for downtown San Francisco [3], which it expects will lead to 21% reduction in vehicle delay, \$60M-\$80M annual net revenue, and 20-25% transit speed improvement. In light of the LCCC experience, and the lack of traffic data in downtown San Francisco, one can only be sceptical of the announced benefits.

As an alternative to area tolls, the MIT Future Urban Mobility program in Singapore [62] suggests using a token system to allow cars into congested areas of the city. There is a limited pool of tokens, and they are issued on the first-come, first-served basis through a mobile application that uses geo-location information. Once the car leaves the critical area, its token is released back into the pool. The advantage of the scheme is its flexibility: the number of tokens can be changed by area and time of use. One could treat exceptions, e.g. residents could be guaranteed a token. One can also imagine implementing dynamic cordon pricing, in which tokens may be acquired for a fee that depends on the number of tokens left in the pool. The token scheme presupposes that a non-token holding car is easily identified, making enforcement costs low. So the scheme would work well in Singapore where every car has an electronic tag, but less well in other places.

The area toll presupposes that congestion is due to excess demand. But as we noted in Section 2.2 capacity and demand for an area are problematic notions.[18] Furthermore, it is quite likely that traffic control inside the congestion zone is far from efficient, so the small net benefits of area tolls may easily be realized through better traffic control.

Affecting modal split Programs providing information and incentives to help people learn and use their transportation options, supported by emerging technologies and services may prove to be more effective techniques of demand management than tolls. Such programs include establishing bicycle-friendly facilities and environments, including dedicated bicycle lanes, secure bicycle storage areas and showers [9]; promoting park-and-ride facilities, where commuters and others can leave their

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[18] For instance, [60] uses an explicit speed-flow relationship which assumes (without justification) that traffic is homogeneous inside the congestion zone.

vehicles and transfer to a bus, rail system (rapid transit, light rail, or commuter rail), or carpool for the remainder of the journey [1]; subsidizing travel costs for residents [11]; and dynamic pricing for parking spaces based utilization [61]. A 2009 study conducted by UC Berkeley researchers for Caltrans showed that 5% of travelers were shifting mode from car to train as a result of travel time information displayed on changeable message signs (CMS), which was displayed only when travel time on a train was estimated to be shorter than that on a freeway [47].

Corporate shuttles are proliferating. Companies such as Apple, Box, eBay, Facebook, Genentech, Google, Intuit, bus their employees to and from work, noticeably reducing the number of cars on the roads [33]. In San Francisco alone, employee shuttles conduct 35,000 rides per day according to the city's Municipal Transportation Agency (MTA) [29], and their number continues to grow as other companies join the trend. Apartment postings for sale and rent regularly tout proximity to corporate shuttle stops.

Car sharing services (Zipcar, Car2Go, City Carshare) are extending their presence. Ride on demand and rideshare services (Uber, Lyft, SideCar, Zimride) and peer-to-peer car rental (Getaround, RelayRides) are gaining traction. All promote the idea of a car being constantly in motion instead of idly parked. Other new services getting popular are grocery delivery (AmazonFresh, Safeway, Google Shopping Express) and food delivery from restaurants (Eat24, SpoonRocket). Although these concepts are not new, they are experiencing a rebirth due to the massive adoption of internet and mobile applications. Increased use of such delivery services, as well as ridesharing, leads to fewer cars on the roads and reduced need for parking. For example, MIT researchers showed through simulations that ridesharing has the potential of cutting total vehicle population in Singapore by a factor of 4 to 5 [10].[19]

Telecommuting is also an important factor affecting demand. Based on the analysis of 2012 American Community Survey data, 2.6% of the U.S. workforce (3.3 million people, not including the self-employed or unpaid volunteers) work from home, an 80% increase since 2005 [31]. According to October 2011 Ipsos/Reuters survey of employees from 24 countries, 17% of them telecommute on a frequent basis. The research based on 2001-2009 National Household Surveys (NHTS), indicates, however, that although telecommuting changes the travel pattern, it does not necessarily reduce demand, and that employing telecommuting as a demand management tool is questionable [78].

4 Conclusion

The purpose of transportation management is to improve:

1. mobility through minimization of congestion;
2. environment through fuel economy and lower emissions;
3. safety by reducing human errors in driving on the road; and
4. parking by reducing the number of idle vehicles.

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[19] These are achievable targets: compare Hong Kong with a population of 7.1M per capita income of $33K, and 464K private vehicles with Singapore's 5.4M, income $34, and 520K private vehicles; only 10 percent of trips in Hong Kong use private cars according to the Hong Kong Transport Department.

To fight congestion, one has to assess its severity and cause. As discussed in Section 1, at present such assessment is crude and untrustworthy, because it relies on traffic speed measurements alone. Speed measurements are adequate for travel time estimation, but to compute demand, delay and productivity of a traffic network, vehicle (and passenger) counts need to be systematically collected. This shows the need to invest in sensing infrastructure able to measure traffic volumes.

Congestion is caused by (1) inefficient traffic control, and/or (2) excess demand. When one experiences traffic congestion without an obvious reason, such as an accident or some sort of special event at a certain location, it is impossible to tell which of the two is the cause. Traffic data 'X-rays' (Figures 2 and 3 in Section 2) help determine that: large fluctuations of delay and productivity for the same demand indicate poor traffic control as the cause of congestion.

The best traffic control algorithms rely on traffic state feedback, where the state is estimated from available measurements (Section 3.1). To make the state estimation more reliable, traffic volumes must be measured. Feedback control with inaccurate feedback may produce more harm than no control at all. Here again, we emphasize the need for proper sensing infrastructure.

Optimizing traffic control should occur before demand management through pricing. Doing it in reverse order leads to severe underutilization of the road network, as was illustrated by the Interstate 680 HOT lane example (Section 3.2). In the long run, the most effective demand management techniques are likely to be the ones affecting travelers' mode choices.

Autonomous vehicles will soon appear on our roads and are expected to significantly change the transportation landscape. Combined with emerging ride on demand and rideshare services they are likely to solve the excess demand problem (at least, partially), and to improve safety on roads by reducing drivers' errors. There will also be less need for parking. It seems dubious to imagine, however, that autonomous cars will do away with the need for traffic control. On the contrary, their success relies on efficient traffic control. Only if they believe that by driving themselves they will not reach their destination sooner and safer, will today's drivers turn into tomorrow's passengers.

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References

[1] 511 Rideshare. 511 Rideshare Website. `http://rideshare.511.org`.

[2] A. de Palma and R. Lindsey. Traffic congestion pricing methodologies and technologies. *Transportation Research Part C*, 19:1377–1399, 2011.

[3] Association of Bay Area Governments and Metropolitan Transportation Commission. Draft Plan Bay Area, Strategy for a Sustainable Region, March 2013.

[4] B. Bilger. Auto correct: Has the self-driving car at last arrived? The New Yorker, 11/25/2013.

[5] California Department of Tranportation. PeMS homepage. `http://pems.dot.ca.gov`.

[6] California Department of Transportation. California high-occupancy vehicle lane degradation action plan, 2013.

[7] California Transportation Commission. Corridor Mobility Improvement Account Program Guidelines. `http://www.dot.ca.gov/hq/transprog/ibond/CMIA_Guidlelines_Adopted.pdf`, accessed January 6, 2014.

[8] C.D.Cottrill, F.C. Pereira, F. Zhao, I.F. Dias, H.B. Lim, M. Ben-Akiva, and P.C. Zegras. The future mobility survey: Experiences in developing a smartphone-based travel survey in Singapore. *92nd Annual Meeting of the Transportation Research Board, Washington, D.C., USA*, (Paper 13-4849-2), 2013.

[9] Chicago Department of Transportation. Chicago Streets for Cycling Plan 2020, 2012.

[10] J. Chu. New algorithm finds best routes for one-way car sharing. *MIT News Office*, June 23, 2013. `http://web.mit.edu/newsoffice/2013/algorithm-finds-best-routes-for-one-way-car-sharing-0624.html`.

[11] City of Emeryville Shuttle. Emery Go-Round. `http://www.emerygoround.com`.

[12] Alameda County Transportation Commission. I-680 Southbound Express Lane, Annual Report FY2010-2011, n.d.

[13] Alameda County Transportation Commission. I-680 Southbound Express Lane, Annual Report FY2011-2012, n.d.

[14] TRB Freeway Operations Committee. The future of travel time data-a paradigm shift. A discussion Paper prepared for the TRB Regional Transportation System Management and Operations Committee and the AASHTO Subcommittee on System Operations and Management Task Force on Traveler Information, 2004.

[15] N. Congress. Smart road, smart car: The automated highway system. *Public Roads, Magazine of the Federal Highway Administration*, 60(2), 1996. `http://www.fhwa.dot.gov/publications/publicroads/96fall/p96au46.cfm`.

[16] J. Dargay, D. Gately, and M. Sommer. Vehicle ownership and income growth, worldwide: 1960-2030. *Energy Journal*, 28(4):143–170, 2007.

[17] DARPA Grand Challenge. `http://en.wikipedia.org/wiki/DARPA_Grand_Challenge`.

[18] C. Davies. Mobileye wants self-driving cars by 2016 at a fraction of google's costs. *SlashGear.com*, May 30, 2013.

[19] Deloitte. Connected Vehicles Enter the Mainstream. `http://www.deloitte.com/view/en_US/us/Industries/Automotive-Manufacturing/c3ae03df93428310VgnVCM1000001956f00aRCRD.htm`.

[20] G. Dervisoglu, G. Gomes, J. Kwon, A. Muralidharan, P. Varaiya, and R. Horowitz. Automatic calibration of the fundamental diagram and empirical obsevations on capacity. *88th Annual Meeting of the Transportation Research Board, Washington, D.C., USA*, 2009.

[21] C. Diakaki, M. Papageorgiou, and T. McLean. Integrated Traffic-Responsive Urban Corridor Control Strategy in Glasgow, Scotland. *Transportation Research Record*, (1727):101–111, 2000.

[22] DKS Associates. Interstate 80 Integrated Corridor Mobility Project: Final Corridor System Management Plan, 2010.

[23] R. Dowling and S. Ashiabor. Traffic signal analysis with varying demands and capacities, Draft Final Report. Technical Report NCHRP 03-97, Transportation Research Board, 2012.

[24] M.K. Ekbatani, A. Kouvelas, I. Papamichail, and M. Papageorgiou. Congestion control in urban networks via feedback gating. *Transportation Research, Part B*, 46:1393–1403, 2012.

[25] S Elmer. BMW targets 2020 for self-driving cars. *AutoGuide*, February 26, 2013.

[26] Federal Highway Administration. 11th International Conference on High-Occupancy Vehicle Systems Conference Proceedings, October 2002, Seattle, WA. Technical Report FHWA-OP-03-100, Washington DC, 2003.

[27] FHWA. Focus on congestion relief. www.fhwa.dot.gov/congestion/describing_problem.htm, accessed December 25, 2013.

[28] FHWA. Demo '97: Proving AHS Works. *Public Roads*, 61(1), 1997.

[29] L. Gannes. San Francisco May Crack Down on Corporate Shuttle Buses. *AllThingsD*, July 21, 2013. `http://allthingsd.com/20130721/san-francisco-may-crack-down-on-corporate-shuttle-buses`.

[30] N. Geroliminis and C. F. Daganzo. Existence of urban-scale macroscopic fundamental diagrams: Some experimental findings. *Transportation Research Part B*, 42(9):759–770, 2008.

[31] Global Workplace Analytics. The State of Telework in the U.S. `http://www.globalworkplaceanalytics.com/telecommuting-statistics`.

[32] Google Driverless Car. `http://en.wikipedia.org/wiki/Google_driverless_car`.

[33] Google Green. Google Sustainable Commute. `http://www.google.com/green/efficiency/oncampus`.

[34] J. Holmes. Volvo says autonomous car convoys could be reality by 2020. *MotorTrend*, May 24, 2011.

[35] ITS International. Benefits of Florida's traffic signal retiming, 1/4/2013.

[36] D. Johnson. Audi predicts self-driving cars by 2020. *Left Lane News*, January 30, 2013.

[37] Joint Transport Research Centre. Managing urban traffic congestion: Summary document. Technical report, OECD, 2007. ISBN 978-92-821-0128-5.

[38] E. Koukoumidis, L-S Peh, and M. Martonosi. SignalGuru: Leveraging mobile phones for collaborative traffic signal schedule advisory, 2012. Mobisys'12.

[39] A. A. Kurzhanskiy and P. Varaiya. Guaranteed prediction and estimation of the state of a road network. *Transportation Research, Part C*, 21:163–180, 2012.

[40] J. Kwon and P. Varaiya. Effectiveness of California's High Occupancy Vehicle (HOV) system. *Transportation Research, Part C*, 16(1):98–115, 2008.

[41] Legislative Analyst's Office. HOV lanes in California: Are they acheiving their goals?, January 2000. `www.lao.ca.gov/2000/010700_hov/010700_hov_lanes.html`.

[42] H. Liebenstein. Allocative efficiency vs. x-efficiency. *American Economic Review*, 56(3):392–415, 1966.

[43] J.A. Lindley. Applying systems engineering to implementation of adaptive signal control technology. ITS World Congress, 2012.

[44] H.K. Lo. A cell-based traffic control formulation: Strategies and benefits of dynamic timing plans. *Transportation Science*, 35(2):148–164, 2001.

[45] T. Lomax, D. Schrank, and B. Eisele. The 2012 Annual Urban Mobility Report. Technical report, Texas Transportation Institute, 2003. `http://mobility.tamu.edu`.

[46] P. Mirchandani and L. Head. A real-time traffic signal control system: architecture, algorithms, and analysis. *Transportation Research, Part C*, 9:415–432, 2001.

[47] A. Mortazavi, X. Pan, E. Jun, and M Odioso. Travel Times on Changeable Message Signs Volume II — Evaluation of Transit Message Signs. Technical Report UCB-ITS-CWP-2009-2, California Center for Innovative Transportation, University of California, Berkeley, 2009.

[48] A. Muralidharan. *Tools for modeling and control of freeway networks*. PhD thesis, University of California, Berkeley, 2012.

[49] National Traffic Operations Coalition. 2012 National Traffic Report Card, 2012. `http://www.ite.org/reportcard/`.

[50] NHTSA. Crash factors in intersection-related crashes: An on-scene perspective. Technical Report DOT HS 811 366, National Highway Traffic Safety Administration, 2010.

[51] S. Nichols. Google wants some form of self-driving cars on roads by 2018. *TechRadar*, February 11, 2013.

[52] C. Osorio and M. Bierlaire. A multiple model approach for traffic signal optimization in the city of Lausanne. In *Swiss Transport Research Conference*, 2008. `http://www.strc.ch/conferences/2008/2008_Osorio_Bierlaire_TrafficSignalOptimization.pdf`, accessed August 15, 2009.

[53] C. Osorio and M. Bierlaire. An analytic finite capacity queueing network model capturing the propagation of congestion and blocking. *European Journal of Operational Research*, 196:996–1007, 2009.

[54] M. Papageorgiou, C. Diakaki, V. Dinopoulou, A. Kotsialos, and Y. Wang. Review of road traffic control strategies. *Proceedings of the IEEE*, 91(12):2043Ũ–2067, December 2003.

[55] M. Papageorgiou, H. Hadj-Salem, and J. Blosseville. ALINEA: a local feedback control law for on-ramp metering. *Transportation Research Record*, 1320:58–64, 1991.

[56] I. Papamichail, M. Papageorgiou, V. Vong, and J. Gaffney. HERO Coordinated Ramp Metering Im- plemented at Monash Freeway, Australia. *89th Annual Meeting of the Transportation Research Board, Washington, D.C., USA*, 2010.

[57] A. Pascale and M. Nicoli. Adaptive Bayesian network for traffic flow prediction. In *IEEE Statistical Signal Processing Workshop (SSP)*, pages 177–180, 2011.

[58] PB Americas, Inc. *Regional HOT lanes network feasibility study: Task 3–Initial assessment report. Prepared for Metropolitan Transportation Commission and California Department of Transportation.* 2007. `http://www.mtc.ca.gov/planning/hov/Task_3_report_FINAL.pdf`.

[59] I. Preisinger. Daimler aims to launch self-driving car by 2020. *Reuters*, September 8, 2013.

[60] G. Santos and G. Fraser. Road pricing: lessons from London. *Economic Policy*, pages 265–310, April 2006.

[61] SF Park. `http://sfpark.org/`.

[62] Singapore-MIT Alliance for Research and Technology. Future Urban Mobility. `http://smart.mit.edu/research/future-urban-mobility/future-urban-mobility.html`.

[63] S. Sunkari. The benefits of retiming traffic signals. *ITE Journal*, pages 26–29, April 2004.

[64] TOPL. TOPL homepage, 2008. `http://path.berkeley.edu/topl/`.

[65] S. Tsugawa. A history of automated highway systems in Japan and future issues, 2008.

[66] University of Texas, Austin. Computer scientist developing intersections of the future with fully autonomous vehicles. `http://www.utexas.edu/news/2012/02/20/autonomous_intersection`.

[67] U.S. Government Accountability Office. Traffic Congestion: Road Pricing Can Help Reduce Congestion, but Equity Concerns May Grow. Technical Report GAO-12-119, Report to the Subcommittee on Transportation, Housing, and Urban Development and Related Agencies, Committee on Appropriations, House of Representatives, 2012. `http://www.gao.gov/products/GAO-12-119`.

[68] US House of Representatives. `http://www.washingtonwatchdog.org/documents/cong_reports/house/109_203.html`.

[69] P. Varaiya. The case for top. `http://gateway.path.berkeley.edu/topl/pp/100225_PravinVaraiya__TOPL_Presentation.pdf`.

[70] P. Varaiya. Max pressure control of a network of signalized intersections. *Transportation Research, Part C*, 36:177–195, 2013.

[71] P. Varaiya. HOT tips, July 2008. `http://paleale.eecs.berkeley.edu/~varaiya/papers_ps.dir/HOT-2.pdf`.

[72] W.S. Vickery. Pricing in urban and suburban transport. *American Economic Review*, 53(2):452–465, May 1963.

[73] R. Waters. Tesla moves ahead from google in race to build self-driving cars. *The Financial Times*, 17 September, 2013.

[74] J. B. White. Nissan expects to market self-driving cars by 2020. *Wall Street Journal*, August 27, 2013.

[75] Wikipedia. Hans Monderman. `http://en.wikipedia.org/wiki/Hans_Monderman`, accessed January 6, 2014.

[76] X-F. Xie, S. F. Smith, L. Lu, and G. J. Barlow. Schedule-driven intersection control. *Transportation Research, Part C*, pages 168–189, 2012.

[77] J. Yoon, B. Noble, and M. Liu. Surface street traffic estimation, 2007. Mobisys'07.

[78] P. Zhu. *Telecommutting, travel behavior and residential location choice: can telecommuting be an effective policy to reduce travel demand?* Phd thesis, University of Southern California, 2011.