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Implementing technology to improve public highway performance: A leapfrog technology from the private sector is going to be necessary

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ABSTRACT

Policymakers could implement available, well-tested technologies to improve the efficiency of highway pricing, investment, and operations, which would improve travel speeds, reliability, and safety and reduce highway expenditures. Unfortunately, political and bureaucratic impediments to implement such technology exist and are unlikely to be overcome in the near future. However, technological innovations underway in the private sector, especially the driverless car, are likely to eventually leapfrog the technology that the public highway authorities could and should implement and will enable road users to obtain most of the potential benefits from technological advances in highway travel.

1. Introduction

The nation's road system is vital to the U.S. economy. Valued at close to $3 trillion, according to the Bureau of Economic Analysis of the U.S. Department of Commerce, 75 percent of goods, based on value, are transported on roads by truck, 93 percent of workers' commutes are on roads by private automobiles and public buses, and by far the largest share of non-work and pleasure trips are taken by road (Winston, 2013). Indeed, roads can be accurately characterized as the arterial network of the United States.

Unfortunately, the arteries are clogged: the benefits that commuters, families, truckers, and shippers receive from the nation's road system have been increasingly compromised by growing congestion, vehicle damage, and accident costs. The Texas Transportation Institute's latest *Urban Mobility Report* puts the annual cost of congestion to the nation, including both travel delays and expenditures on fuel, at more than $100 billion. Despite frustratingly frequent lane closures for road repairs, federal and state highway agencies' expenditures cannot seem to outpace the rate of road-infrastructure deterioration. Data from the Federal Highway Administration's annual publication *Highway Statistics* indicate that although the condition of the nation's highways and bridges varies with general economic conditions, as much as one-third of the nation's highways may be in poor or mediocre condition, and one-quarter of the nation's bridges may be functionally obsolete or structurally deficient. Driving on damaged roads is estimated to cost U.S. motorists $80 billion in additional annual operating costs and vehicle repairs (The Road Information Program, 2013) and has also been shown to damage trucks and increase their operating costs. Finally, although highway safety has improved during the past few decades, because of greater enforcement of drunken driving laws, improvements in vehicle safety, and other factors, traffic fatalities are still one of the leading causes of non-disease deaths in the United States, exceeding more than 30,000 lives annually.

Economists have repeatedly pointed out that policymakers have failed to address highway inefficiencies by implementing efficient road pricing for cars and trucks and by making efficient investments based on cost-benefit analyses.[1] And they have tried to understand the political and institutional impediments to implementing efficient highway policies, and have suggested ways to overcome them, but inefficient policies persist (Winston, 2013).

In this paper, we take a different perspective and argue that policymakers could implement available, well-tested technologies to make highway pricing, investment, and operations more efficient, which would improve travel speeds, travel-time reliability, and safety and reduce highway expenditures. Indeed, in contrast to the technological advance in the comfort, performance, and safety of the vehicles that use the roads, which may reach new heights with the development of the driverless car, technological improvements in the way roads are priced, designed, constructed, and operated have been relatively modest. A technology-based approach to improving highway performance would be particularly attractive because innovations

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[1] Mohring and Harwitz (1962) developed a model of efficient long-run pricing and investment rules for highways that provided the foundation for research in this area. Recent models of highway pricing and investment have accounted for demand uncertainty, lumpy investment, heterogeneous users, and so on (Lindsey, 2012).

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that increase efficiency have taken on renewed importance in today's slow-growth economy.

Unfortunately, the aforementioned political and institutional impediments also apply to implementing new technology on public highways and they are unlikely to be overcome in the near future. However, the private sector is developing new technological innovations, especially the driverless car, which will eventually leapfrog the technology that the public highway authorities could and should implement today, thus providing road users with most of the potential benefits from technological advances in highway travel.

2. Highway characteristics and technologies that could improve performance

Highways provide capacity to allow a flow of different types of vehicles, including passenger cars, buses, and heavy trucks, to travel simultaneously and they are designed to provide a specified level of durability to bear the weight of different vehicles, particularly heavy trucks, and to resist surface wear and structural damage to pavements and bridges. Technologies that help expand capacity and increase durability can increase the flow of traffic and the effective lifetime of a highway (before resurfacing or reconstruction is needed).

Capacity is a function of speed limits, the number and width of lanes and shoulders, and other factors; it is reached well after the road has become congested. Economists characterize congestion as occurring when vehicle speeds decline from free-flow speed, which is the observed speed when traffic-flow is light. The Transportation Research Board (2010) has determined that freeways have a capacity of 2400 passenger-cars/hr/lane with a free-flow speed of 70 mi/hr while freeways have a capacity of 2250 passenger-cars/hr/lane with a lower free-flow speed of 55 mi/hr. As greater traffic volume causes the road's capacity to eventually be reached, speeds on those freeways fall to 53.3 miles/hr and 50 miles/hr, respectively.[2] Additional traffic then causes the density of vehicles to exceed freeway capacity creating an unstable traffic flow, which is characterized by stop and go traffic. Traffic engineers define this outcome as "hyper-congested conditions," in which travel speeds can decline rapidly.

For freeways, the preceding travel conditions are summarized in Fig. 1 in terms of the relationship between speed and traffic flow (in passenger-cars/hr/lane). The speed-flow relationship has been shown empirically to be parabolic; thus, two speeds are generally possible for every given flow: one in uncongested or congested conditions (traffic densities less than or equal to 45 passenger-cars/mile/lane); the other in hyper-congested conditions (traffic densities greater than 45 passenger-cars/mile/lane). For the same level of traffic flow, the portion of the curve in hyper-congested conditions results in a much slower traffic speed than does the portion of the speed-flow curve in uncongested or congested conditions. Transportation officials in many metropolitan areas attempt to prevent motorists from experiencing hyper-congested conditions on freeways by, for example, putting stop and go signals on on-ramps to slow the flow of additional traffic.

Durability depends on pavement thickness, material composition, and other factors such as drainage and climate, as well as on the bridge design. Pavements become worn as the cumulative number of vehicles passing over them rises, and they eventually require resurfacing or reconstruction. Damage caused by a vehicle to the pavement depends on its weight per axle, rather than on its total vehicle weight. The damage caused by an axle is defined in

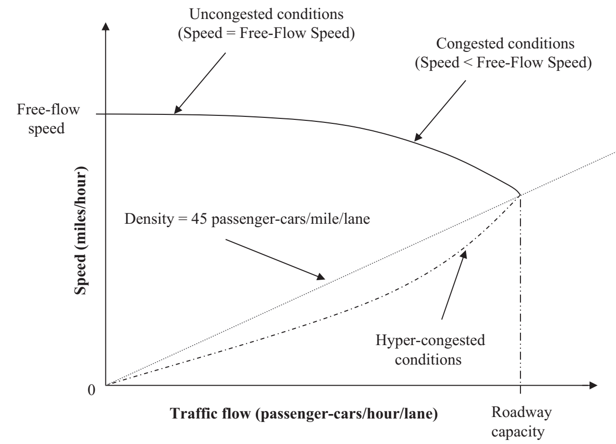

Fig. 1. Illustration of the parabolic speed-flow relationship for freeways.

terms of the number of "equivalent single-axle loads" (ESALs) causing the same damage; the standard is a single axle of 18,000 pounds. Small and Winston (1988) found that the damage caused by a heavily-loaded vehicle rises with the third power with its load. Almost all pavement damage tends to be caused by trucks and buses because, for example, the rear axle of a typical 13-ton trailer causes over 1000 times as much pavement damage as that of a car.

Bridges become stressed as the cumulative number of heavy vehicles passing over them increases and they need to be rehabilitated before they experience catastrophic failure, as in the Minneapolis incident in 2007 that resulted from additional vehicle weight on a bridge that exacerbated a design flaw. The bridge wear that is caused by a truck depends on its total vehicle weight, roughly in proportion to its third power (Moses et al., 1987).

Private and public enterprises enhance their efficiency by implementing technologies that are the products of their research and that have been developed by other entities. The Federal Highway Administration (FHWA) appears to have foreclosed the first option because its budget devotes only a small amount of funds for research and development. Specifically, $400 million of its roughly $40 billion fiscal year 2013 budget is allocated under research programs, but only half of that amount actually funds promising research and development. In contrast, FHWA's administrative expenses exceed $450 million.[3]

New general purpose communication technologies (Bresnahan and Trajtenberg, 1995) as well as specific highway and vehicle technologies give highway authorities the opportunity to make more efficient use of the current vehicle-carrying capacity and durability of public highways by setting accurate marginal cost prices for road users and by adjusting investments and operations to respond to real-time variations in highway travel demand. General purpose technologies include global positioning system (GPS) satellite navigation services that, among other things, collect information about motorists, such as their location and speed, and that can suggest alternative routings for their journeys; Bluetooth signals that can be detected to monitor the speed of cars and trucks throughout the road system in real time in order to assist drivers' route choice decisions and to adjust traffic signal timing; and mobile software applications (apps) and websites that provide motorists with real-time information about driving conditions throughout a highway network and about available parking spaces. Motorists are becoming increasingly aware of the benefits of GPS systems that provide real-time traffic information; accordingly, the share of cars on the road that are equipped with those

[2] At capacity, density for freeways is 45 passenger-cars/mile/lane regardless of free-flow speed (Mannering and Washburn, 2013; Transportation Research Board, 2010).

[3] Those figures are from http://www.fhwa.dot.gov/map21/ha.cfm.

services is expected to climb from 10 percent as of 2013 to 50 percent by 2015.[4]

Specific highway and vehicle technologies include weigh-in-motion capabilities, which provide real-time information to highway officials about truck weights and axle configurations that they can use to set efficient pavement-wear charges and to enforce safety standards efficiently; adjustable lane technologies, which allow variations in the number and width of lanes in response to real-time traffic flows; new vehicle attributes, such as automatic vehicle braking that could decrease vehicle headways and thus increase roadway capacities; improved construction and design technologies to increase pavement life and to strengthen roads and bridges; and photo-enforcement technologies that monitor vehicles′ speeds and make more efficient use of road capacity by improving traffic flows and safety.

3. Technologies to improve pricing and to reform truck size and weight limits

Gasoline taxes, which are currently used to charge motorists and truckers for highway travel, do not vary appropriately with their vehicles′ contributions to congestion or with truck axle-weights that contribute to pavement wear. Thus the highway authority should set congestion tolls and charges for pavement and bridge wear to close the gap between the social and private costs of highway travel and to make more efficient use of available highway capacity and durability.

Until recently, however, highway authorities have not had satisfactory technology to determine and efficiently collect accurate charges for motorists′ and truckers′ road use. Vickrey (1963) initially proposed to implement congestion pricing by equipping all cars with an electronic identifier that would be scanned by roadside equipment. But the technology had questionable accuracy at the time and involved substantial transactions costs of creating records that would be assembled into bills that would be mailed to motorists for payment. Today, technology is available for highway authorities to eliminate the transactions costs associated with human toll collectors who are still used on some roads and to collect accurate congestion, pavement, and bridge wear charges electronically at low cost to them and road users.[5]

3.1. Congestion pricing

Because federal policymakers have been unwilling to seriously consider raising fuel taxes, they have been desperately trying to find additional sources of highway funding to finance construction of new roads and additional lanes. But as we know from Downs (1962), peak-hour congestion rises to meet maximum capacity because of latent demand—that is, travelers who used less preferred routes, modes, and times of day shift to the newly constructed thoroughfares. Downs′ Law would not apply, however, if policymakers set tolls that adjusted in real-time to traffic flows and congestion because some motorists who previously avoided highly congested highways and local streets would be discouraged from using those thoroughfares by their initial tolls, while others would be discouraged by higher tolls if traffic became more congested.

The informational requirements to set an optimal congestion toll τ_l (on highway link l in a road network consisting of L links) can be gleaned from its mathematical expression. For a given volume of traffic v_l per unit of time, the toll that a highway authority should set is expressed as (Lindsey, 2012):

$$\tau_l = \frac{\partial c_l(v_l, K_l)}{\partial v_l} v_l, \quad \boldsymbol{l} \in \boldsymbol{L} \tag{1}$$

where c_l is the user cost function, which includes the private costs of a trip, such as fuel consumption and other vehicle operating costs like depreciation, as well as travel time costs, and K_l is the link′s vehicle-carrying capacity per unit of time.

The highway authority can determine the traffic volume on a specific stretch of road during a given time interval by using GPS navigation services and then draw on plausible cost estimates that are available in the empirical literature (e.g., Small and Verhoef, 2007) to set the specific charge, which it can communicate to motorists on their apps before they reach the tolling area so they can decide whether to take the tolled route based on their preferred combination of out-of-pocket costs and travel time. Those motorists who do so would have their highway account reduced by the amount of the charge electronically via their vehicle transponders, without their journeys being disrupted or their privacy invaded.[6] In sum, by implementing available technologies, a highway authority would have the necessary traffic information to set efficient tolls throughout the day and motorists would be able to obtain the pricing and routing information that they would need to optimize their journeys.

Langer and Winston (2008) estimated that by substantially reducing—but not eliminating—delays and by reducing residential sprawl (because the out-of-pocket costs of commuting would no longer be underpriced), congestion pricing in major metropolitan areas could generate annual gains of $40 billion, accounting for the travel time savings for commuters, savings for taxpayers from lower costs of public services from greater residential density, and greater revenues to the government. By also improving travel-time reliability, which Small et al. (2005) have found to be valued by motorists as much as they value reductions in average travel time, the benefits from congestion pricing would be even greater.[7]

Information technology could also facilitate efficient pricing of highway shoulders and curb parking. Because automakers have continued to improve vehicle reliability in recent years, breakdowns rarely occur today and the benefits to motorists from opening a shoulder to increase highway capacity and reduce congestion are likely to exceed the cost of limiting space for vehicle incidents. To get a feel for the potential benefits, we use the Bureau of Public Roads (BPR) formula, which determines travel time on a road accounting for delays due to congestion. The BPR formula shows that opening a shoulder to traffic (in the peak travel direction) on a four-lane freeway that normally operates with a traffic flow of 90% of highway capacity would reduce motorists′ travel time by roughly one-third (Mannering and Washburn, 2013).[8] Pricing the shoulder efficiently would produce additional travel time savings.[9] As noted, motorists could use an app to have knowledge in advance of whether the shoulder was open to traffic and the price to drive on it.

[4] This forecast is from Jim Bak of Inrix, a provider of traffic software and data, as reported in Steve Hargreaves, "You're Getting Stuck in Traffic Less," *CNN Money*, February 5, 2013.

[5] Fleming (2012) argues that the collection costs of electronic tolling are quite low, in the vicinity of 5% of the revenue collected using proven methods and technology.

[6] To maintain privacy, the highway authority could send motorists a monthly summary of the deductions from their account without any information indicating the time and the part of the highway they used.

[7] Small, Winston, and Yan found that the value that motorists place on the standard deviation of travel time (or the difference between two fractiles of the distribution of travel time) was similar to the value they place on average travel time.

[8] The BPR formula for travel time on a highway link is given by $t_l = t_{fl}\,[1 + \alpha(v_l/K_l)^{\beta}]$, where t_l is the travel time on highway link l in minutes; t_{fl} is the free-flow travel time on this link in minutes; v_l is the traffic volume on the link in minutes; K_l is the capacity of the link in vehicles per hour; and α and β are parameters that respectively take the values of 1.1491 and 6.8677 for freeways.

[9] Minneapolis has begun to explore this policy by introducing "dynamic priced shoulder lanes" on Interstate 35.

For the majority of their trips, including work trips, motorists face sub-market prices for on-street parking; thus, they incur search costs themselves when looking for parking spaces while also imposing significant costs on other drivers by adding to congestion on surrounding local streets (Shoup, 2005). Field studies suggest that as much as one-third of traffic in some parts of New York City and Los Angeles is attributable to drivers circling as they hunt for vacant parking spaces and extrapolations from those studies suggest that nationwide costs are in the billions of dollars.[10]

Efficient pricing for parking spaces reduces congestion on local streets by reducing motorists′ incentive to search for scarce on-street spaces (which is spurred by the price difference between underpriced on-street and costly off-street parking), and by increasing the turnover of street spaces, which reduces the search time required to find a vacant space. As before, GPS navigation services could determine traffic levels on local streets; based on that traffic, real time prices could be set at parking meters; and motorists could use apps to determine the availability of parking spaces and their prices. San Francisco, Chicago, and Los Angeles are currently conducting experiments that set prices for on-street parking that vary by location and time of day, while also making information on meter rates and vacant spaces available in real time. Pierce and Shoup (2013) provide evidence that San Francisco′s pilot pricing program is allocating parking spots more efficiently by narrowing the variation in on-street parking occupancy rates across the city.

3.2. Pavement and bridge wear pricing

Because pavement damage is related to a truck′s weight per axle and bridge stress is related to a truck′s total weight, efficient highway prices for trucks should encourage truckers to reduce those weights whenever possible. An efficient short-run marginal cost pavement-wear charge, *SRMC*, encourages truckers to reduce their ESALs. The informational requirements to set this charge can be gleaned from its mathematical expression, which is given per ESAL mile as (Small and Winston, 1988):

$$SRMC = \frac{\alpha C(W)}{N(D)}, \tag{2}$$

where α is a parameter, $C(W)$ is the cost of resurfacing a highway of width W, as measured by the number of lanes, and $N(D)$ is the lifetime of a road of durability D, as determined by the number of ESALs that can pass over it before it must be resurfaced.

A highway authority can estimate a truck′s ESAL miles by using high-speed weigh-in-motion (WIM) technologies. WIM uses sensors that are installed in one or more traffic lanes to identify a vehicle and record its number of axles, vehicle load, and journey while it continues to travel in the traffic stream (Jacob, 2010). The total charge would then be sent to the truck′s owner as the product of the truck′s ESAL miles and a plausible estimate of the resurfacing costs per ESAL mile. Small et al. (1989) estimate that replacing the fuel tax with an axle-weight (marginal cost) charge would encourage truckers to shift to vehicles with more axles that do less damage to road pavements, thereby reducing maintenance expenditures and producing annual welfare gains exceeding $12 billion (in 2013 dollars).

WIM could also be used to measure the considerable stress caused by trucks crossing a bridge (National Cooperative Highway Research Program, 2003) and to determine efficient bridge-wear charges as a function of vehicle weight and bridge-age; the latter influence is important because older bridges become more susceptible to heavy loads as a result of metal fatigue and possible age-related deterioration of concrete reinforcing bars (Barker and Puckett, 2007). Based on their planned routings, trucks could determine their charges online and reduce them by either reducing their loads or by taking alternative routings to avoid higher-priced bridge crossings. As a result, bridges would last longer and the likelihood of unexpected catastrophic bridge failure, expensive repairs, and the loss of life would be less.

3.3. Truck size and weight limits

Truck size and weight limits have been established to keep trucks that might cause excessive pavement/bridge damage and jeopardize safety off of certain roads. At the same time, those limits raise the costs of trucking operations by requiring truckers to disrupt their journeys to stop at weigh stations for vehicle inspections, and by forcing trucking companies to use smaller trucks to make additional trips to move the nation′s freight. WIM technologies would enable highway authorities to accurately monitor truck sizes and weights, which would eliminate inspections at weigh stations. And information technology that facilitates more efficient highway pricing could spur vehicle design improvements, such as stronger brakes that would allow trucking companies to use larger trucks with more axles to reduce average operating costs without compromising safety.[11]

McKinnon (2005) provides some illustrative evidence from the United Kingdom that relaxing truck size and weight limits could significantly increase trucking productivity and reduce social costs. He estimated that increasing maximum truck weights 6700 lbs (a modest 7.3 percent increase over the previous weight limits) resulted in trucking-industry annual operating-cost savings of nearly $250 million (in 2013 dollars), and by significantly reducing vehicle-miles traveled, reduced congestion and greenhouse gas emissions. Similarly, the U.S. surface freight transportation system stands to increase its efficiency without necessarily increasing the costs of trucking accidents by implementing technology that permits more flexible and higher truck size and weight limits.

4. Technologies to improve highway investments in capacity and durability

At first blush, investments to expand highway vehicle-carrying capacity and to increase durability appear to be very expensive undertakings. But technology could be implemented to enable certain investments to improve those highway characteristics at modest cost.

Ng and Small (2012) point out that most highways in major metropolitan areas operate in congested conditions during much of the day, yet highway design standards are based on free-flow travel speeds. Highway authorities could effectively expand capacity during peak travel periods to reduce delays by adjusting the number and width of lanes on a freeway in response to real-time traffic volumes that are measured by GPS navigation services. Thus to enable vehicles to move faster, heavy traffic volumes would call for more but narrower lanes, while lighter traffic volumes would

[10] As reported in *Time*, "The New Science of Parking," July 9, 2007, Transportation Alternatives, a New York advocacy group, conducted a 2006 field study of 15 blocks in the upper west side of New York City and Professor Donald Shoup of UCLA conducted a study of Westwood Village in Los Angeles. The studies estimated that motorists′ search for on-street parking over a one year period in those locations respectively generated 366,000 and 950,000 additional vehicle miles traveled. Given the thousands of locations throughout U.S. metropolitan areas where such search occurs and applying Small and Verhoef′s (2007) estimate of the social marginal cost of a vehicle mile of $1.08, suggests an estimate of parking-search costs in the United States in the billions of dollars.

[11] Truckers have responded to higher operating costs by adopting improvements in vehicle design. For example, in response to higher fuel prices, some truckers increased their vehicles′ fuel economy by using the TrailerTail, developed by ATDynamics, to reduce the aerodynamic drag generated at the rear of a trailer.

call for fewer but wider lanes. Technology exists to install lane dividers that can be illuminated so that they are visible to motorists, and that can also be adjusted in response to traffic volumes to increase or decrease the number of lanes that are available. As noted in the case of opening a highway shoulder to traffic, creating an additional lane during peak travel periods would result in substantial travel time savings for motorists. And although it would be easier and less costly to install variable lane widths for new roads than for existing roads, implementing this technology whenever possible would be less expensive than constructing an additional lane that meets standard width requirements, especially for freeways in dense urban areas where land is scarce and adding to road capacity is a very expensive proposition.

The rapid evolution of material science (including nanotechnologies) has produced advances in construction materials, construction processes, and quality control that have significantly improved pavement design, resulting in greater durability, longer lifetimes, lower maintenance costs, and less vehicle damage caused by potholes. For example, Little et al. (1997) estimated that the SUPERPAVE effort in the late 1980s and 1990s (Transportation Research Board, 2005), which developed new asphaltic binder specifications for repaving, produced roughly $0.6 billion (in 2013 dollars) in such benefits. Other investments that apply recent advances in material-science technologies are also possible, but they are often delayed because state Departments of Transportation try to minimize their expenditures rather than the sum of those and highway users′ costs and because they award contracts on the basis of the minimum bid, not on the technological sophistication of the contractor (Winston, 2010).

Finally, state Departments of Transportation have been slow to implement advances in roadway structural monitoring technologies that would allow them to monitor the health of both pavements and bridges on a continuous basis, providing valuable information for optimal repair and rehabilitation strategies that could reduce the cost of highway services (Lajnef et al., 2011).

5. Highway operations that affect safety

The large benefits of highway travel have been tempered by the recurring social costs of vehicle accidents, which have been estimated by Cambridge Systematics (2011) to be roughly $300 billion for major urban areas in 2009. Both automakers and highway authorities have attempted to reduce those costs. Automakers have continued to make automobiles safer since they first introduced them to the public by improving vehicle design and structural strengthening, installing seat-belts, anti-lock brakes, and air bags, and the like. Recent safety innovations include electronic stability control, warning and emergency braking systems, speed alerts, and mirrors with blind spot warnings, which will also increase road capacity by enabling vehicles to travel closer together without compromising speed.[12] Policymakers and highway authorities have attempted to promote safety by setting speed limits, instituting traffic signals, enforcing traffic laws, and responding to traffic incidents. Technologies could be implemented to improve the effectiveness of those actions.

Lave and Lave (1999) concluded that Congressional action that set a national maximum speed limit of 55 miles/h in 1974, but subsequently abolished it in 1996 and allowed states to set their own maximum speed limits, showed that higher speed does not necessarily kill. Instead, they concluded that it showed lives could be saved by setting speed limits that people would obey because they were aligned with driving conditions. Accordingly, highway authorities could implement technology to improve safety and reduce travel times by setting variable speed limits (VSLs) that are properly aligned with real-time traffic flows and other driving conditions such as weather. Papageorgiou et al. (2008) found that VSLs displayed on roadside variable message signs have led to substantial improvements in safety in many countries; evidence that they improve highway safety in the United States also exists (Washington State Department of Transportation, 2007).

The traffic control system in most U.S. cities was developed by inexperienced public officials when the automobile was a new mode of transportation. Todd (2004) points out that in many driving situations, all-way stops and roundabouts would be more effective than traffic signals in reducing motorist and pedestrian fatalities, as well as in reducing traffic delays. To add to the problem, poor signal timing and coordination, often caused by outdated signal control technology or reliance on obsolete data on relative traffic volumes (Atkinson and Castro, 2008), contributes to some 300 million vehicle hours of annual delay on major roadways (National Transportation Operations Coalition, 2007). Technology that enables traffic signals to respond to real-time traffic flows by optimizing the duration of traffic signals and the use of flashing-red signals at intersections when they are lightly used and by providing a warning signal to stopped motorists at intersections of an impending green light to reduce start-up delays could be more widely applied to enhance safety and reduce travel times. Start-up delays amount to about 6 percent of the time that a traffic-signal is green at a typical intersection. Mannering and Washburn (2013) estimate that cutting those delays in half could reduce the delays caused by signals nearly 20 percent, with little effect on safety.

Finally, the costs of enforcing traffic safety laws, which include high-speed police chases that occasionally result in fatal accidents, could be substantially reduced by using photo-enforcement technology (roadside cameras) to identify and issue citations to motorists who run stop signs or traffic signals, or who exceed the speed limit by a predetermined amount, such as 15 miles/h. Shin et al. (2009) evaluated an experiment in Arizona and found that automated speed enforcement on only a 6.5 mile stretch of freeway in Scottsdale reduced enforcement costs as much as $17 million per year.[13]

Vehicle incidents (accidents and disablements) account for a large share of traffic congestion and they can be very costly.[14] Garrison and Mannering (1990) estimated that the average per-minute cost in travel time delays of an incident on Seattle freeways was $3500 (in 2013 dollars). Highway authorities could make much greater use of communications technology to reduce those costs and help accident victims receive assistance more quickly by detecting disruptions in traffic flows and speeds that indicate an incident has occurred. Incident response teams, including tow trucks to remove the disabled vehicle(s), could then be quickly alerted and dispatched, while motorists on the road could be notified of disruptions and advised to avoid the troubled area and to make way for response teams that are addressing the problem. Wilde (2013) estimated that a one-minute increase in response time could increase the victim-mortality rate as much as 17 percent;

[12] Currently, highway design standards assume that the capacity of a freeway with a 70 miles/h free-flow speed is 2400 passenger cars per hour per lane (with a speed at capacity of 53.3 miles/h), which is based on the observation that drivers typically leave roughly 100 feet when following another car at that speed. Technologies, such as those noted in the text, which could halve that distance would result in a substantial increase in capacity—to roughly 4300 passenger cars per hour per lane (assuming an average car length of 16.5 feet).

[13] Photo-enforcement technology has encountered legal challenges in some but not all states.

[14] The Federal Highway Administration puts the share as high as 25 percent, http://ops.fhwa.dot.gov/program_areas/reduce-non-cong.htm, while the Texas Transportation Institute′s Urban Mobility Report puts the share closer to 50 percent, http://mobility.tamu.edu.

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hence, reducing response times could potentially save the lives of many motorists involved in accidents.

6. Impediments to implementing highway technology

Technological innovations have long been recognized as a major source of economic growth and improved living standards, but analysts have been hard-pressed to explain how they can be spurred by policymakers. In the case of highways, however, policymakers are clearly impeding technological change by failing to implement recent innovations that could significantly improve the speed, reliability, and safety of motorists′ trips, while reducing the cost of highway services. In Table 1, we summarize the positive effects on travel and highway authorities′ budgets that could be achieved if those technologies were implemented. Unfortunately, empirical estimates of many of their benefits are either not available or based only on limited experiments. As a naïve accounting exercise based on the available national estimates that we reported previously and on plausible extrapolations of the estimates in the case studies we noted, we estimate that the aggregate annual benefits amount to at least $100 billion.

Table 1
Beneficial actions that could be facilitated by implementing technology.

Action	Effects on travel and highway authorities
Pricing	
Congestion pricing on lanes for cars and trucks	• Travel time savings, increased revenue, reduced sprawl • More reliable travel times
Congestion pricing on shoulders for cars	• Can reduce travel times as much as one-third • Increase in revenues
Real-time pricing and information on available spaces for on-street parking	• Reduce search costs and congestion and increase revenue
Pavement-wear pricing for trucks	• Reduce maintenance expenditures
Bridge-wear pricing for trucks	• Reduce the likelihood of catastrophic failure, fatalities, bridge repairs
Truck size and weight limits	
Monitor truck sizes and weights without manual inspections and have more flexible size and weight limits	• Improve trucking productivity
Investments	
Adjust number of traffic lanes in response to traffic volumes	• Can reduce travel times as much as one-third
New pavement design procedures to increase pavement durability	• Extend pavement lifetimes, reduce maintenance costs and vehicle damage
Safety operations	
Variable speed limits	• Improve traffic flows and safety
Retime and optimize traffic signaling	• Improve traffic flows and safety
Introduce photo-enforcement technology	• Reduce the cost and improve the effectiveness of enforcement
Expedite response to incidents	• Reduce delays • Increase safety

Why has the public sector failed to implement those technologies in a timely manner to realize the large benefits? Winston (2010) argues that the federal government is biased toward the status quo in managing and operating the nation′s transportation system because of agency limitations, regulatory constraints, and political forces. In the case of the Federal Highway Administration, it may lack the expertise to ensure that technologies to improve the highway system are implemented effectively and efficiently. Indeed, we noted that FHWA′s budget does not place a priority on developing new technologies to improve highways. Like other agencies, FHWA may also be risk-averse and want to avoid the mistakes and well-publicized delays in implementing new technology that, for example, have tarnished the Federal Aviation Administration′s reputation to manage air traffic control effectively.

From a political perspective, implementing the latest technology may be helpful in overcoming highway users′ opposition to certain policies such as congestion and pavement wear pricing. Until recently, the public understandably conceived of road pricing as requiring human toll collectors, which forces motorists to waste time in a line at a toll booth, to pay a fee that could realistically be interpreted simply as a revenue raising device that is sensitive to the political election cycle (Finkelstein, 2009). Motorists have indicated that they value the option to pay an electronic toll to expedite their trips as indicated by the growing adoption in several metropolitan areas of the country, such as Atlanta, Los Angeles, Salt Lake City, and Washington, D.C., of high-occupancy-toll lanes, where solo motorists can pay a toll to travel in a less-congested carpool lane. As more motorists use GPS services to expand their route choice options, they may become more enthusiastic about comprehensive road pricing, especially if prices and travel times vary on different lanes to cater to motorists′ heterogeneous preferences for travel time and reliability (Small et al., 2006). In response to political pressures, policymakers could reduce charges on a given lane to selected users, such as carpoolers and low-income travelers, via smaller deductions on their transponders.

Trucking interests have been able to dissuade policymakers from significantly reforming truck charges despite repeated protests from railroad and automobile interests that the fuel tax does not fully charge trucks for their fair share of highway costs. WIM technologies would make the trucking industry′s highway costs more transparent and may eventually break the stalemate among the modal interests, while truckers′ resistance to reforming truck charges might be lessened if they were given greater flexibility in their choices of trailer sizes and loads that they could carry.

We speculate that although implementing new technologies could help address political impediments to efficient pricing, transportation officials continue to maintain status quo policies because they fear certain users′ objections to higher charges and because FHWA may not stand to gain much from technology that reduces the cost of building and maintaining highways if those savings lead to reductions in its budget. Accordingly, we must look to the private sector to implement technology that could improve highway travel.

7. Leapfrog technology from the private sector

If the public sector is unlikely to make a substantial effort to implement new technology to improve highway performance, it is useful to consider the private sector′s potential to do so. One of the major benefits of intercity transportation deregulation was that it freed railroads, trucking companies, and airlines to develop and implement technologies that the federal government′s economic regulations had thwarted for decades (Gallamore, 1999; Morrison and Winston, 1999). It is therefore hardly surprising that the government has impeded technological advance in public highways and quite possible that the private sector could spur an advance if given an opportunity.

One possibility may be public-private partnerships (PPPs) involving highways, such as the Indiana toll road, which have been initiated during the past few decades. Future partnerships could include a requirement in the contract that the private operator has to install the latest technology (under penalty of a fine) to improve pricing, investment, and safety operations. Unfortunately, many PPPs have been compromised by flawed contracts that have been poorly designed and have had to be renegotiated (Engel et al., 2011), while others have suffered financial problems from the Great Recession. Thus, it appears unlikely that PPPs will be a source of significant technological advance in highway services at any time in the near future.

Fortunately, more encouraging private-sector highway travel innovations are underway. The most promising is the recent revelation of the "driverless" car, which does a human driver's normal job and much more, and has raised the possibility of an entirely new era of highway transportation. Driverless cars are operated by computers that obtain information from an array of sensors on the surrounding road conditions, including the location, speed, and trajectories of other cars. The on-board computers gather and process information many times faster than the human mind can process it. By gathering and reacting immediately to real-time information, and by eliminating concerns about risky human behavior such as distracted and impaired driving, the technology has the potential to prevent collisions and greatly reduce highway fatalities, injuries, vehicle damage, and costly insurance. And it can significantly reduce delays and improve travel-time reliability by creating a smoother traffic flow and by routing and, when necessary, rerouting drivers who have programmed their destinations.

Driverless trucks are also in the developmental stage. For example, dozens of such trucks are being used to haul materials at an iron-ore mine in Australia and at other locations away from public thoroughfares. In addition to contributing to improved traffic flows and motorists' safety, driverless trucks would benefit industry by substantially reducing labor costs, insurance, and operating costs.

Thus far, seven states—including California, Florida, and Nevada—have legalized the testing of driverless cars, and several other states are considering doing the same.[15] Competition among automakers and other firms to develop the best technology is already underway. Google has logged nearly 500,000 miles testing its version of a driverless car; General Motors is working on a model with researchers at Carnegie Mellon University; Audi, BMW, Toyota, and Volvo have demonstrated their driverless models; and Nissan has claimed that it will offer a full line of driverless cars in the next decade. In short, some, admittedly optimistic, forecasts indicate that driverless cars could be a common sight on U.S. roads by 2025.

Empirical estimates of their benefits are sparse but one study (Fagnant and Kockelman, 2013) shows that they are highly dependent on the speed of adoption and extent of market penetration. Those authors account for the reduction in fatalities and injuries, less vehicle damage, and savings in travel time, fuel, and parking costs and estimate that even a modest 10% penetration of driverless cars would generate annual benefits of $40 billion. Annual benefits amount to an eye-popping $200 billion if market penetration reaches 50%.

The optimum social outcome would call for a combination of investments by the public sector, to improve highway infrastructure technology, and by the automakers and other private sector firms, to perfect driverless car technologies. We have argued, however, that it is unlikely that this outcome would be achieved because the public sector will not make the required investments in the near future to improve highway infrastructure technology; in contrast, the private sector is clearly determined to perfect and implement driverless cars. Thus driverless car technologies are quite likely to effectively leapfrog most of the existing technologies that the public sector could but has failed to implement to improve highway travel. Driverless vehicles would significantly expand the capacity of the highway system and reduce delays and congestion for all aspects of travel including parking; greatly reduce the probability of vehicle accidents and their associated costs; and the driverless technologies adopted by truckers could potentially reduce the damage to pavements and bridges by adjusting routings and delivery times to avoid the most vulnerable infrastructure and to decrease congestion that strains bridges.

Driverless vehicles are inevitable but the major obstacle to motorists and firms from adopting them as soon as possible is whether the government will take prudent and expeditious approaches to help resolve important questions about assigning liability in the event of an accident, the availability of insurance, and safety regulations. The National Highway and Traffic Safety Administration (NHTSA), which is responsible for regulating automobile safety, has issued cautious recommendations about driverless cars. That may be appropriate at this stage of the vehicle's development, but NHTSA should also be cautious about sharing FHWA's legacy of not promoting timely innovation in highway travel.

8. Conclusion

Kahneman and Krueger (2006) report evidence that over the course of the day individuals' commutes are the leading activity for which their dominant emotion is negative. Motorists would probably feel even worse if they were aware of the evidence summarized here—that policymakers could implement available technology on the road system that would reduce much of the congestion and delays that make road travel so onerous and would also improve safety.

Our discussion of policymakers' failure to implement this technology has culminated in the eternal debate over whether the public or the private sector is better able to spur technological change that contributes to growth. In the case of highways, we conclude that it is likely that the private sector will eventually implement driverless car technologies, and that those technologies will benefit motorists by leapfrogging the technological advance that the public sector has put on hold. If this innovation is not impeded by government regulations and does succeed, social welfare could possibly increase further by exploring privatization of the road system so that it could operate at the same level of technological sophistication as the vehicles that are driven on it.[16]

References

Atkinson, Robert D., Castro, Daniel D., 2008. Digital Quality of Life: Understanding the Personal and Social Benefits of the Information Technology Revolution. Information and Technology Foundation, Washington, D.C.

Barker, Richard, Puckett, Jay, 2007. Design of Highway Bridges: An LRFD Approach, second edition John Wiley & Sons, New York, NY.

Bresnahan, Timothy F., Trajtenberg, M., 1995. General Purpose Technologies: 'Engines of Growth'? J. Econom. 65 (1), 83–108.

Cambridge Systematics, 2011. Crashes vs. Congestion: What's the Cost to Society?, Prepared for the American Automobile Association, November.

[15] Smith (2012) argues that driverless cars are legal in the United States and discusses the issues involved in determining their legality.

[16] Winston and Yan (2011) indicate competitive conditions under which highway privatization would improve motorists' welfare.

Downs, Anthony, 1962. The law of peak-hour expressway congestion. Traffic Q. 16 (3), 393–409.
Engel, Eduardo, Fischer, Ronald, Galetovic, Alexander, 2011. Infrastructure PPPs: When and How, Draft Book Manuscript, Department of Economics. Yale University, New Haven, CT.
Fagnant, Daniel J., Kockelman Kara M., 2013. Preparing a Nation for Autonomous Vehicles Eno Center for Transportation, Washington, DC.
Finkelstein, Amy, 2009. E-ZTax: tax salience and tax rates. Q. J. Econ. 124 (3), 969–1010.
Fleming, Daryl S., 2012. Dispelling the myths: toll and fuel tax collection costs in the 21st century. Reason Found. Policy Study 409.
Gallamore, Robert E., 1999. Regulation and innovation: lessons from the american railroad industry. In: Gomez-Ibanez, Jose A., Tye, William B., Winston, Clifford (Eds.), Essays in Transportation Economics and Policy: A Handbook in Honor of John R. Meyer. Brookings, Washington, DC. (pp. 493–529).
Garrison, D., Mannering, F., 1990. Assessing the traffic impacts of freeway incidents and driver information. ITE J. 60 (8), 19–23.
Jacob, Bernard, 2010. Weigh-in-Motion for Road Safety, Enforcement, and Infrastructure. LCPC, Paris, France.
Kahneman, Daniel, Krueger, Alan B., 2006. Developments in the Measurement of Subjective Well-Being. J. Econ. Perspect. 20 (1), 3–24.
Lajnef, N., Rhimi, M., Chatti, K., Mhamdi, L., Faridazar, F., 2011. Toward an integrated smart sensing system and data interpretation techniques for pavement fatigue monitoring. Comput.-Aided Civil Infrastruct. Eng. 26 (6), 513–523.
Langer, Ashley, Winston, Clifford, 2008. Toward a comprehensive assessment of road pricing accounting for land use. Brook.-Whart. Pap. Urban Aff., 127–175.
Lave, Charles, Lave, Lester, 1999. Fuel economy and auto safety regulation: is the cure worse than the disease. In: Gomez-Ibanez, Jose A., Tye, William B., Winston, Clifford (Eds.), Essays in Transportation Economics and Policy: A Handbook in Honor of John R. Meyer. Brookings, Washington, DC. (pp. 257–289).
Lindsey, Robin, 2012. Road Pricing and Investment. Econ. Transp. 1 (1), 49–63.
Little, D.N., Memmott J., McFarland F., Goff Z., Smith R., Wootan C.V., Zollinger D., Tang T., Epps J., 1997. Economic Benefits of SHRP Research. Texas Transportation Institute. Available in PDF from TRIS Online at: ⟨http://trisonline.bts.gov/search.cfm⟩.
Mannering, Fred L., Washburn, Scott S., 2013. Principles of Highway Engineering and Traffic Analysis, fifth edition John Wiley and Sons, New Jersey.
McKinnon, Alan C., 2005. The economic and environmental benefits of increasing maximum truck weight: the British experience. Transp. Res. Rec. Part D 10 (1), 77–95.
Mohring, Herbert, Harwitz, Mitchell, 1962. Highway Benefits: An Analytical Framework. Northwestern University Press, Evanston, Illinois.
Morrison, Steven, Winston, Clifford, 1999. Regulatory reform of U.S. intercity transportation. In: Gomez-Ibanez, Jose A., Tye, William B., Winston, Clifford (Eds.), Essays in Transportation Economics and Policy: A Handbook in Honor of John R. Meyer. Brookings, Washington, DC. (pp. 469–492).
Moses, Fred, C. Schilling, K. Raju, 1987. Fatigue Evaluation Procedures for Steel Bridges. National Cooperative Highway Research Program Report 299, November, National Research Council, Washington, D.C.
National Cooperative Highway Research Program, 2003. Effect of Truck Weight on Bridge Network Costs. Report 495, Transportation Research Board, Washington, D.C.
National Transportation Operations Coalition, 2007. Executive Summary: 2007 National Traffic Signal Report Card, Washington, D.C.
Ng, Chen Feng, Small, Kenneth A., 2012. Tradeoffs among free-flow speed, capacity, cost, and environmental footprint in highway design. Transportation 39 (6), 1259–1280.
Papageorgiou, M., E. Kosmatopoulos, I. Papamichail, 2008. Effects of variable speed limits on motorway traffic flow, Transportation Research Record 2047, Journal of the Transportation Research Board, pp. 37–48.
Pierce, Gregory, Shoup, Donald, 2013. Getting the prices right: an evaluation of pricing parking by demand in San Francisco. J. Am. Plan. Assoc. 79 (1), 67–81.
Shin, K., Washington, S., Schalkwyk, Ida van, 2009. Evaluation of the city of Scottsdale loop 101 photo enforcement demonstration program. Accid. Anal. Prev. 41 (3), 393–403.
Shoup, Donald, 2005. The High Cost of Free Parking. Planners Press, Chicago.
Small, Kenneth A., Verhoef, Erik T., 2007. The Economics of Urban Transportation. Routledge Publishers, London.
Small, Kenneth A., Winston, Clifford, 1988. Optimal highway durability. Am. Econ. Rev. 78 (3), 560–569.
Small, Kenneth A., Winston, Clifford, Evans, Carol A., 1989. Road Work: A New Highway Pricing and Investment Policy. Brookings Institution, Washington, D.C.
Small, Kenneth A., Winston, Clifford, Yan, Jia, 2005. Uncovering the Distribution of Motorists′ Preferences for Travel Time and Reliability. Econometrica 73 (4), 1367–1382.
Small, Kenneth A., Winston, Clifford, Yan, Jia, 2006. Differentiated road pricing, express lanes, and carpools: exploiting heterogeneous preferences in policy design. Brook.-Whart. Pap. Urban Aff., 53–96.
Smith, Bryant Walker, 2012. Automated Vehicles are Probably Legal in the United States. The Center for Internet and Society, Stanford University, Palo Alto, CA.
The Road Information Program, 2013. Bumpy Roads Ahead: America′s Roughest Rides and Strategies to Make our Roads Smoother, Washington, D.C., October.
Todd, Kenneth, 2004. Traffic Control: An Exercise in Self-Defeat. Regulation Magazine 27 (3), 10–12.
Transportation Research Board, 2010. Highway Capacity Manual. National Research Council, National Academies, Washington, DC.
Transportation Research Board, 2005. Superior Performing Asphalt Pavement: SUPERPAVE, Performance by Design, Final Report of the TRB SUPERPAVE Committee, National Academies, Washington, DC.
Vickrey, William S., 1963. Pricing in urban and suburban transport. Am. Econ. Rev. 53 (2), 452–465.
Washington State Department of Transportation, 2007. Active Traffic Management (ATM) Feasibility Study, Available from: ⟨http://psrc.org/assets/524/ATMfeasiblitystudy.pdf⟩.
Wilde, Elizabeth Ty, 2013. Do Emergency medical system response times matter for health outcomes? Forthcom. Health Econ. , http://dx.doi.org/10.1002/hec.2851.
Winston, Clifford, 2013. On the performance of the U.S. transportation system: caution ahead. J. Econ. Lit. 51 (3), 773–824.
Winston, Clifford, 2010. Last Exit: Privatization and Deregulation of the U.S. Transportation System. Brookings Institution, Washington, D.C.
Winston, Clifford, Yan, Jia, 2011. Can privatization of U.S. Highways improve motorists′ welfare? J. Public Econ. 95 (7–8), 993–1005.