Preliminary Investigation

Caltrans Division of Research, Innovation and System Information

Effectiveness of Efforts to Reduce Greenhouse Gas Emissions by Improving Transportation System Efficiency and Pavement Conditions

Requested by
Garth Hopkins, Division of Transportation Planning

October 31, 2014

The Caltrans Division of Research, Innovation and System Information (DRISI) receives and evaluates numerous research problem statements for funding every year. DRISI conducts Preliminary Investigations on these problem statements to better scope and prioritize the proposed research in light of existing credible work on the topics nationally and internationally. Online and print sources for Preliminary Investigations include the National Cooperative Highway Research Program (NCHRP) and other Transportation Research Board (TRB) programs, the American Association of State Highway and Transportation Officials (AASHTO), the research and practices of other transportation agencies, and related academic and industry research. The views and conclusions in cited works, while generally peer reviewed or published by authoritative sources, may not be accepted without qualification by all experts in the field.

Table of Contents

Executive Summary

Background

The state of California and Caltrans are committed to combating climate change impacts through the reduction of greenhouse gas (GHG) emissions. The Division of Traffic Operations and the Division of Transportation Planning jointly requested this Preliminary Investigation of representative research and successful state DOT practices aimed at reducing transportation-related GHG emissions. Caltrans is particularly interested in learning about research and practices that have shown measurable connections between specific actions taken and GHG emission reductions realized (investment vs. benefit). As the agency builds and manages highways in the future, Caltrans would like to incorporate considerations of GHG emissions as well as safety, constructability and mobility.

To help address this need, CTC conducted a literature search to identify completed and in-progress research and other relevant publications on reducing GHG emissions caused by transportation. We also conducted interviews with representatives at Oregon and Washington State DOTs to identify successful state DOT practices.

Our research focused on:

1. Traffic management strategies to reduce congestion and therefore emissions, including ramp metering, traffic light synchronization and arterial signal control, changeable message signs, loop detectors, closed circuit television cameras, demand management, smart land use, value pricing, and active lane management.

2. Effect of pavement condition (such as smoothness, hardness and rolling resistance) on greenhouse gas emissions, with a focus on research showing quantifiable reductions in fuel consumption, such as correlation with International Roughness Index (IRI) measures.

Summary of Findings

Consultation with State DOTs

We contacted Oregon DOT and Washington State DOT about their efforts to reduce greenhouse gas emissions and whether they had quantified the effectiveness of those efforts.

ODOT has developed GreenSTEP, a modeling tool for predicting the emissions benefits of transportation policies, including those related to ITS and transportation demand management: http://www.oregon.gov/ODOT/TD/TP/pages/greenstep.aspx

WSDOT was not able to provide information on quantifying the effectiveness of emissions reduction efforts, but did provide a comprehensive overview of its efforts in this area and contacts for further information. Of note are WSDOT's efforts to:

- Install 15 new roundabouts (WSDOT currently has 124) by June 30, 2015.
- Install 17 ramp meters to improve flow, improve system efficiency, reduce accidents and relieve traffic congestion on Interstate 5 in Tacoma beginning in summer 2014 (see http://www.wsdot.wa.gov/projects/i5/sr510congestmgmt/).

- Prepare an agency greenhouse gas emissions inventory in summer 2014. A final report will be submitted to the state Department of Ecology in fall 2014, per a 2009 state law (http://apps.leg.wa.gov/rcw/default.aspx?cite=70.235.050).

Related Research and Resources

We conducted a literature review of the effects on emissions of (1) improvements in transportation system efficiency and (2) pavement conditions, including smoothness and rolling resistance. This review relies in part on a report developed for Caltrans, *Near-Term Transportation Energy and Climate Change Strategies: Interregional Transportation Related Greenhouse Gas Emissions Reduction Strategies* (see **Multiple Strategies**), and reviews much of the same literature (as well as other and more recent literature).

<u>System Efficiency</u>

We found a large quantity of research assessing the effectiveness of strategies to reduce transportation emissions by increasing system efficiency. These assessments generally rely on transportation modeling to estimate emissions effects from mobility data. Overall, a USDOT report estimates the collective impact of transportation efficiency strategies to be modest compared to vehicle fuel technology strategies, accounting for a possible 3 to 6 percent reduction relative to baseline 2030 transportation emissions (see *Transportation's Role in Reducing U.S. Greenhouse Gas Emissions* in **Multiple Strategies**). *Quantifying Greenhouse Gas Mitigation Measures* (see **Multiple Strategies**) estimates the reduction in CHG emissions of specific strategies for improving traffic flow at between 0 and 45 percent.

Of special significance is FHWA's *Reference Sourcebook for Reducing Greenhouse Gas Emissions from Transportation Sources* (see **Multiple Strategies**), which has a comprehensive literature review on estimated emissions reductions from various strategies.

Land Use

According to the FHWA *Sourcebook*, research suggests that doubling residential density across a region could reduce vehicle miles traveled (VMT) by about 5 to 12 percent, and a recent report found that by shifting 60 percent of new residential growth across the United States to compact patterns, carbon dioxide (CO_2) emissions could decline by 7 to 10 percent from current trends by 2050, or 79 million metric tons of carbon dioxide ($MTCO_2$) annually.

Quantifying Greenhouse Gas Mitigation Measures (see **Multiple Strategies**) provides a summary of the estimated reduction in CHG emissions for various land use strategies, including .8 to 30 percent for increasing density, and 10 to 65 percent for increasing location efficiency.

Integrated Corridor Management

A 2013 study estimated that integrated corridor management projects in San Diego, Dallas and Minneapolis would lead to annual fuel savings of 323,000, 981,000, and 17,600 gallons, respectively, correlating to 6 million, 17.6 million, and 316,800 lbs of annual CO_2 reductions for the three sites (see *Integrated Corridor Management Using ITS*).

Transportation Demand Management (General)

- A 2014 Mineta Transportation Institute study estimates that distance-based vehicle pricing could reduce greenhouse gas emissions from vehicle miles of travel by about 16 percent (*see Active Travel Co-Benefits of Travel Demand Management Policies That Reduce Greenhouse Gas Emissions*).

- A 2013 report from Germany found that reducing traffic demand by 20 percent led to about a 23 percent reduction in CO_2, nitrogen oxides (NOx), and particulate matter (PM10) emissions (see *Reducing Local Traffic Emissions at Urban Intersection Using ITS Countermeasures*).
- A 2011 U.S. Environmental Protection Agency (EPA) report includes a chart estimating the effect of transportation demand management alone or in combination with other strategies (see *Potential Changes in Emissions Due to Improvements in Travel Efficiency*).

Road Pricing/HOT Lanes

The FHWA *Sourcebook* concludes that where road pricing has been employed in practice, before-and-after studies have found that vehicle miles traveled were reduced by between 2 and 10 percent, and that where measured, GHGs declined by 2 to 6 percent. For instance, a study modeling tolls for various English cities found reductions in CO_2 emissions of 1.4 to 14.2 percent, with most in the range of 2 to 4 percent. And a study of the San Francisco Bay Area's proposed regional high-occupancy toll (HOT) lane network estimated it would result in 7 percent lower CO_2 emissions during the morning peak hours than a high-occupancy vehicle (HOV) lane network in the same corridors.

Quantifying Greenhouse Gas Mitigation Measures (see **Multiple Strategies**) estimates the reduction in CHG emissions of road pricing at between 7.9 and 22 percent.

Parking Management and Pricing

The FHWA *Sourcebook* notes that there is substantial evidence from empirical studies of U.S. parking scenarios that charging for parking reduces single-occupancy vehicle trips by 7 to 15 percent. Parking fees instituted in Perth in 1991 contributed to an estimated annual reduction of 1.7 million gallons of gasoline and 17,000 $MTCO_2$.

Quantifying Greenhouse Gas Mitigation Measures (see **Multiple Strategies**) provides a summary of the estimated reduction in CHG emissions for various parking management and pricing strategies, including 12.5 percent for limiting parking supply, 2.6 to 13 percent for unbundling parking costs from property costs, and 2.8 to 5.5 percent for implementing market price public parking.

Car Sharing

According to the FHWA *Sourcebook*, studies in the United States and Canada have found that emissions declined on average by between 0.8 and 1.2 $MTCO_2$ annually per car sharing member, even after accounting for those members who drive more often because they did not previously own vehicles. For instance, a recent study based on survey responses from over 6,200 car sharing members in North America found that on average, a household reduces its GHG by 0.84 $MTCO_2$ per year after joining car sharing. *Quantifying Greenhouse Gas Mitigation Measures* (see **Multiple Strategies**) estimates the reduction in CHG emissions for car sharing at .4 to .7.

HOV Lanes, Managed Lanes and Ridesharing

The FHWA *Sourcebook* concludes that emissions benefits for HOV lanes and ridesharing vary widely depending on policy and context, and generalizations cannot be made. However, it cites a number of studies, including one in which the state of Washington has estimated that its commute trip reduction program, which includes a variety of travel demand management

initiatives, reduces vehicle miles traveled by 170 million per year, or 680,800 per day, and emissions by 85,700 $MTCO_2$ per year, or 342 $MTCO_2$ per day.

Quantifying Greenhouse Gas Mitigation Measures (see **Multiple Strategies**) provides a summary of the estimated reduction in commute trip CHG emissions for various commute trip reduction strategies, including 1-6 to 2 percent for voluntary commute trip reduction, 4.2 to 21 percent for required commute trip reduction, and 1 to 15 percent for ride sharing programs.

We also found several other studies on the emissions effects of these strategies:

- A study modeling the emissions impacts of HOV and eco-lanes in medium-sized European cities found a reduction in CO_2 of 37 percent (see *Are HOV/Eco-Lanes a Sustainable Option to Reducing Emissions in a Medium-Sized European City?*).

- A 2009 New Zealand report estimated that casual carpooling in San Francisco saves between 0.45 and 0.92 million gallons of gasoline annually, with emission reductions ranging between 4,000 and 8,335 $MTCO_2$ (see *Estimating the Energy Consumption Impact of Casual Carpooling*).

- A Minnesota DOT study found a savings of 4,000 gallons and 3.62 $MTCO_2$ per day from the conversion of HOV lanes back to general-purpose lanes (see *Twin Cities HOV Study, Volume I*).

Traffic Signal Optimization

The FHWA *Sourcebook* concludes that where traffic signal optimization has been implemented and studied, the literature shows 3 to 12 percent fuel savings and consequent reduced GHG emissions at signalized intersections. For instance, in 1983, 41 California cities retimed 1,535 signals, leading in the first year to a reduction of 6.4 million gallons of fuel and 56,898 metric tons of CO_2. Over the next 11 years, 160 California cities and counties retimed 12,245 signals in 334 projects, reducing fuel consumption by 8 percent.

We found numerous other studies that estimate the emissions effects of traffic signal optimization, including:

- One study estimates that traffic signal coordination could reduce emissions by 10 to 40 percent in the most favorable conditions, depending on traffic flow and signal timing settings (*Effects of Traffic Signal Coordination on Noise and Air Pollutant Emissions*.

- A report concludes that traffic light synchronization on the Alicia Parkway in Orange County, California, led to reductions in travel times (11 percent), number of stops (33.3 percent), and greenhouse gases (at least 8,100 lbs) (see *Benefits of Traffic Light Synchronisation*).

- Modeling studies of coordinated signal control in five U.S. localities found reductions in fuel use ranging from no significant change in Seattle to a 13 percent decline in Syracuse, NY (see *Intelligent Transportation Systems Benefits, Costs, Deployment and Lessons Learned: 2008 Update*).

- A study of signal optimization in Nashville, TN, found that retiming 223 signals along seven traffic corridors resulted in fuel use reductions of nearly 6 percent (see *Traffic Signal Optimization Study for the Metro Nashville Signal System*).

Ramp Metering

According to the FHWA *Sourcebook*, the benefits of ramp metering are uncertain, and while some studies report a decrease in emissions, others report an increase due to idling at meters and increased highway speeds. A study of the Twin Cities region in Minnesota found that ramp metering improved mobility, but worsened annual fuel consumption by 5.5 million gallons and produced approximately an additional 50,000 metric tons of CO_2. However, an Oregon study showed a reduction in 4 metric tons of CO_2 daily from 16 fixed-time ramp meters in Portland.

We found several other studies on the emissions effects of ramp metering, including:

- A South Korean study estimating a 7.3 percent net reduction in overall CO_2 emissions, 1,194.9 tons per year, for ramp metering on an overpass (see *An Evaluation of the Ramp Metering Effectiveness in Reducing Carbon Dioxide Emissions*).

- A study estimating that different ramp metering control algorithms would reduce overall fuel consumption by 25 percent (see *ACCEZZ—Adaptive Fuzzy Algorithms for Traffic Responsive and Coordinated Ramp Metering*).

- A report finding only negligible emissions reductions for ramp metering in the San Joaquin valley (*Northern San Joaquin Valley Regional Ramp Metering and High Occupancy Vehicle (HOV) Lane Master Plan*).

Incident Management

According to the FHWA *Sourcebook*, studies of individual urban incident management programs across the United States show varying impacts on GHG emissions, with calculated reductions ranging from 2 to 23 $MTCO_2$ per incident (compared to situations with no incident management). For instance, Maryland's CHART incident management program was estimated to save 4.84 million gallons of fuel on 20,515 incident clearances in 2005, amounting to approximately 235 gallons of fuel and 2 $MTCO_2$ saved per incident.

Roundabouts

According to the FHWA *Sourcebook*, substituting roundabouts for conventional intersections may reduce fuel consumption by 16 to 30 percent and lead to fewer emissions, although these benefits may be entirely negated by emissions from roundabout construction. A study in northern Virginia estimated that converting 10 intersections to roundabouts would save 20,000 gallons of fuel annually per roundabout (equivalent to 177 metric tons of CO_2 per roundabout per year). According to a study of six intersections (five in Kansas and one in Nevada) where roundabouts replaced signalized intersections, the average hourly CO_2 emissions were reduced by 16 percent in peak morning hours and 59 percent in evening hours as compared to the emissions at the site of the intersections that were replaced.

Pavement Conditions

According to the FHWA *Sourcebook*, studies indicate that fuel economy (and consequently GHG differences) can vary between rough and smooth roads between 1 and 10 percent, depending on the type of vehicle and the roughness of the roads considered. For example, in a Missouri study of vehicle performance on roads before and after paving, diesel dump trucks averaged 5.97 miles per gallon before repaving; after paving they averaged 6.11 miles per gallon, a 2.4 percent improvement. However, road resurfacing may not significantly decrease and may even increase GHG emissions because the process of resurfacing roads may produce significant CO_2, possibly more than the amount saved by the resulting smooth roads.

We found a number of other studies estimating the fuel efficiency and emissions effects of pavement roughness, rolling resistance, and other characteristics:

- An ongoing project at the Minnesota Department of Transportation will determine fuel consumption and GHG emissions as a function of pavement deflection (*Verification of Pavement Structure and Deflection Effects on Vehicle Fuel Economy and GHG Emissions*).

- A report estimating that an increase in IRI of 1 m/km (63.4 in/mile) increases fuel consumption of passenger cars by 2 to 3 percent irrespective of speed. For heavy trucks, this increase is 1 to 2 percent at highway speeds (112 km/h or 70 mph) and 2 to 3 percent at low speeds (56 km/h or 35 mph). (See *Estimating Vehicle Operating Costs Due to Pavement Surface Conditions.*)

- A study estimates that 25 percent of the CO_2 emitted on roads is caused by rolling resistance, and 3-5 percent on fuel consumption can be saved by developing and implementing new low rolling resistance pavement types, leading to 45,000 tons less greenhouse gases as CO_2 and 76 tons less nitrogen oxides (NOx) in Denmark alone (*CO_2 Emission Reduction by Exploitation of Rolling Resistance Modeling of Pavements*).

- An NCHRP report includes a useful table summarizing the effects of pavement roughness on fuel consumption (*Estimating the Effects of Pavement Condition on Vehicle Operating Costs*):

Table 7-1. Effect of roughness on fuel consumption.

Speed	Vehicle Class	Base (mL/km)	Adjustment Factors from the Base Value					Base (mpg)	Adjustment Factors from the Base Value				
			IRI (m/km)						IRI (m/km)				
		1	2	3	4	5	6	1	2	3	4	5	6
56 km/h (35 mph)	Medium car	70.14	1.03	1.05	1.08	1.10	1.13	33.53	0.97	0.95	0.93	0.91	0.88
	Van	76.99	1.01	1.02	1.03	1.04	1.05	30.55	0.99	0.98	0.97	0.96	0.95
	SUV	78.69	1.02	1.05	1.07	1.09	1.12	29.89	0.98	0.95	0.93	0.92	0.89
	Light truck	124.21	1.01	1.02	1.04	1.05	1.06	18.94	0.99	0.98	0.96	0.95	0.94
	Articulated truck	273.41	1.02	1.04	1.07	1.09	1.11	8.60	0.98	0.96	0.93	0.92	0.90
88 km/h (55 mph)	Medium car	83.38	1.03	1.05	1.08	1.10	1.13	28.21	0.97	0.95	0.93	0.91	0.88
	Van	96.98	1.01	1.02	1.03	1.04	1.05	24.25	0.99	0.98	0.97	0.96	0.95
	SUV	101.29	1.02	1.04	1.07	1.09	1.11	23.22	0.98	0.96	0.93	0.92	0.90
	Light truck	180.18	1.01	1.02	1.03	1.04	1.05	13.05	0.99	0.98	0.97	0.96	0.95
	Articulated truck	447.31	1.02	1.03	1.05	1.06	1.08	5.26	0.98	0.97	0.95	0.94	0.93
112 km/h (70 mph)	Medium car	107.85	1.02	1.05	1.07	1.09	1.12	21.81	0.98	0.95	0.93	0.92	0.89
	Van	128.96	1.01	1.02	1.03	1.03	1.04	18.24	0.99	0.98	0.97	0.97	0.96
	SUV	140.49	1.02	1.04	1.06	1.08	1.10	16.74	0.98	0.96	0.94	0.93	0.91
	Light truck	251.41	1.01	1.02	1.02	1.03	1.04	9.36	0.99	0.98	0.98	0.97	0.96
	Articulated truck	656.11	1.01	1.02	1.04	1.05	1.06	3.58	0.99	0.98	0.96	0.95	0.94

Gaps in Findings

- The research on the emissions effects of transportation system efficiency improvements seems to rely on computer models to make estimates from mobility data. The level of accuracy of these models is unclear.

- For pavement conditions, research also relies on computer modeling and seems to be limited in scope.

- Our interviews with state departments of transportation did not reveal efforts to quantify emissions benefits of improvements in efficiency or pavement conditions.

Next Steps

Moving forward, Caltrans could consider:

- Exploring ODOT's GreenSTEP model and its use to quantify the emissions effects of transportation policies.

- Following up with contacts provided by WSDOT for further information on the emissions effects of various strategies.

- Following up with MnDOT on the results of its ongoing study, *Verification of Pavement Structure and Deflection Effects on Vehicle Fuel Economy and GHG Emissions*. The study is expected to be complete in October 2014.

Consultation with State DOTs

Below we summarize our conversations with representatives from state departments of transportation about the effectiveness of their emissions reduction efforts.

Oregon

Contacts: Amanda Pietz, Planning Unit Manager, Oregon DOT, 503-986-4227, amanda.pietz@odot.state.or.us.

Tara Weidner, Integrated Transportation Analysis Engineer, Oregon DOT, 503-986-4226, Tara.J.Weidner@odot.state.or.us.

Pietz, who leads ODOT's greenhouse gas reduction planning efforts, referred us to GreenSTEP (http://www.oregon.gov/ODOT/TD/TP/pages/greenstep.aspx), the modeling tool ODOT uses to conduct its analyses and determine what policies to pursue. This model has been adopted at the national level as EERPAT (Energy and Emissions Reduction Policy Analysis Tool; see http://www.planning.dot.gov/FHWA_tool/), and has also served as the basis for several other models.

ODOT's model does not take into account pavement smoothness, but it does account for ITS and TDM. Research leading to ITS inputs in the model can be found on the Portland State University researcher's website at http://alexbigazzi.com/GreenSTEP/.

Pietz referred us to Tara Weidner, ODOT's lead on GreenSTEP, for more details on this model. Weidner said GreenSTEP is a good model for comparing policies at a high level when there are a lot of unknowns. It includes data from TTI's Urban Mobility Report (http://mobility.tamu.edu/ums/). GreenSTEP differs from traditional four-step models (which create demand, distribute demand, model mode choice, and assign routes on the network). The last step is time-consuming, and GreenSTEP does not perform it (and does not need to in order to estimate emissions). GreenSTEP instead creates a lot of detail about households and how much travel people are engaging in and uses this data to determine average vehicle miles traveled per day. Consequently, the model needs data on capacity, population, demand, service miles of transit per capita, and so on. It includes a congestion model that accounts for demand shifts (for instance, from freeways to arterials) depending on circumstances.

In the long run, Weidner said, improving transportation system efficiency has much lower emissions benefits than improving vehicle efficiency.

Washington

Contact: Seth Stark, Sustainable Transportation Manager, Washington State DOT, 360-628-7611, StarkS@wsdot.wa.gov.

We spoke with Seth Stark, WSDOT's Sustainable Transportation Manager. While Stark did not have data on the effectiveness of emissions reduction efforts, he provided information on these efforts along with contact information in several program areas for follow-up by Caltrans:

System Efficiency

Michael Dornfeld
Program Development and Performance Manager
360-705-7288, DornfeM@wsdot.wa.gov

Roundabouts

Brian Walsh
State Traffic Design & Operations Engineer and nationally known roundabout expert
360-705-7986, WalshB@wsdot.wa.gov

Priority actions in the 2013-2015 biennium
- By June 30, 2015, pursue installation of 15 new roundabouts at locations where other types of intersections are being proposed. Roundabouts reduce idling and maintenance costs, increase safety and improve traffic flow. WSDOT currently has 124 roundabouts.

Traffic Management

Bill Legg
State ITS Operations Engineer
360-705-7994, LeggB@wsdot.wa.gov

Focus areas
- Active traffic management signs.
- Traffic management centers.
- Traffic cameras.
- Variable message signs.
- Ramp meters.
- Incident response intervention.
- Traffic light synchronization.

Priority actions in the 2013-2015 biennium
- Complete a Transportation System Management and Operations (TSMO) self-assessment workshop to improve traffic operations, demand management and corridor planning to ensure TSMO capabilities are effectively considered alongside other traditional improvements by summer 2014.

- Install 17 ramp meters to improve flow, improve system efficiency, reduce accidents and relieve traffic congestion on I-5 in Tacoma (http://www.wsdot.wa.gov/projects/i5/sr510congestmgmt/) beginning in summer 2014.

Current efforts
- Reduce idling and traffic delay and prevent secondary collisions through use of WSDOT Incident Response (IR) teams: IR teams responded to 11,333 incidents in the first quarter of 2014, providing $17.4 million in economic benefit ($9.7 million from reduced delay).

- Improve freight mobility: In 2013, WSDOT's commercial vehicle electronic screening program allowed trucks to bypass weigh stations 1.3 million times, saving commercial trucking $13.3 million in operating costs from time savings and about 0.4 gallons of fuel per bypass.

- Use low-cost enhancements (LCE) to improve operational safety and mobility: LCE projects deliver key safety initiatives and provide immediate safety and efficiency improvements. WSDOT delivered 281 LCE projects in the 2011-2013 biennium.

- Toll corridors strategically: Since 2007, WSDOT has strategically tolled corridors to manage congestion, enhance mobility and generate revenue for future improvements.

- Expand travel options:

    o Improve transit options as an aspect of design and construction projects, including intercity passenger rail and bus service and bicycle/pedestrian projects.

    o Expand HOV lanes in Tacoma.

Pavement Conditions

Jeff Uhlmeyer
State Pavement Engineer
360-709-5485, UhlmeyJ@wsdot.wa.gov

Focus areas
- Pavement smoothness.

Highway Lighting

Ted Bailey
State Major Electrical System Design Engineer
360-705-7286, BaileyTe@wsdot.wa.gov

Focus areas
- Highway lighting.

Priority actions in the 2013-2015 biennium
- Research options to increase energy efficiency of highway lighting in 2015.

- Develop a safety predictive model to determine where roadway illumination is justified and where it can be removed without significant impacts to safety and mobility by June 30, 2015.

Current efforts
- Use more energy-efficient lighting to reduce energy consumption:

    o LED lighting can be over 50 percent more energy-efficient than standard lighting and allows dimming and on/off functionality to increase efficiency to nearly 74 percent while maintaining safety.

    o During its projected 15-year life cycle, the Adaptive LED Lighting Pilot Project (http://www.wsdot.wa.gov/Design/Traffic/Electrical/LEDPilotProject) and its Phase 2 expansion could save more than $345,000 in utility and maintenance costs and reduce energy consumption by over 3 million kilowatt hours, saving 2,100 metric tons of carbon dioxide equivalent ($MTCO_2e$).

    o 12 LED projects across all 6 WSDOT regions are underway or recently completed. Plans are being established to identify additional LED retrofit locations.

    o Changing design policy and standards to decrease overall lighting requirements for new projects.

o   Established procurement contracts that provide LED lighting options that benefit all public jurisdictions in the state.

Demand Management

Kathy Johnston
CTR Program Manager
360-709-7925, JohnstK@wsdot.wa.gov

Focus areas
- Commute trip reduction.
- Demand management.

Priority actions in the 2013-2015 biennium
- Submit report to the Legislature on "Demand Management: The Path to Greater Efficiency" (see http://www.wsdot.wa.gov/choices/demand) for the 2014 legislative session.

- In spring 2014, develop and implement WSDOT telework policy and support the Governor's Executive Order 14-02 (http://www.governor.wa.gov/office/execorders/documents/14-02.pdf) to expand telework and flexible work hours.

- In 2014, pilot experimental commute trip reduction (CTR) strategies (http://api.ning.com/files/wBi6IgNyVl8FVQUo9KoyPz7aUXwVL8j*g8REz8GiVrt1p2RzQt YvyZV97q8TWvJhOUn6uGcYjh6Q4pxe51ge8wkCnY4*G8Lt/REVISED_CTRFolio2013_ WEB.pdf) that expand to all trips in Redmond, Seattle, Snohomish County, Spokane County, Tacoma, Tukwila and Yakima.

- Increase the number of approved WSDOT employees that telework at least one day a week from 90 employees in 2013 to 350 by June 30, 2015.

Current efforts
- Update the CTR Program:

  o   Apply lessons learned since 2006 to expand and move toward reduction in all trips.

  o   Update program data methodology that determines effects of CTR on jurisdictions.

- Communicate the benefits of CTR: Pursue integration of CTR into corridor planning.

- Expand telework and use of flexible work hours:

  o   WSDOT invested in videoconferencing and expanded use of web conferencing.

  o   Efforts to meet the goals of Governor's Executive Order 14-02 for promoting flexible work hours.

- Use technology to encourage more efficient commute options: Promote Rideshare Online, a Transportation Demand Management (TDM) technology platform that encourages the use of non-single occupancy vehicle modes.

Construction and Materials

Kurt Williams
Construction and Materials
360-709-5410, WilliKR@wsdot.wa.gov

<u>Focus areas</u>
- Construction.

<u>Priority actions in the 2013-2015 biennium</u>
- Research the use of recycled concrete in new concrete pavements by spring 2014.

- Implement general special provision to allow up to 40 percent reclaimed asphalt binder replacement in pavements, using up to 5 percent recycled roof shingles, in summer 2013.

<u>Current efforts</u>
- Reduce energy use by extending pavement life and investigating alternative paving options:

  o Extend the life of concrete pavements using dowel bar retrofits (http://www.wsdot.wa.gov/NR/rdonlyres/43EF56B4-68AB-4465-87AC-A29826132144/0/DowelBarsfolio_Feb2013Final.pdf)

  o Use the WSDOT Pavement Management System (http://www.wsdot.wa.gov/Business/MaterialsLab/Pavements/PavementManagement.htm) to manage pavement life-cycle costs.

  o Warm-mix asphalt (http://www.wsdot.wa.gov/research/reports/fullreports/789.1.pdf) lowers the mixing temperature of asphalt to reduce compaction temperatures with the goal of saving fuel.

- Reuse roadway materials to reduce energy consumption:

  o Crack sealing (http://www.wsdot.wa.gov/NR/rdonlyres/64439ACD-A71E-47FF-AC5E-A96E90F279EF/0/ppcl01.pdf) and overlay of asphalt on existing concrete pavement base to reduce the need for removal and replacement of existing pavement.

  o WSDOT uses reclaimed asphalt pavement (http://www.wsdot.wa.gov/NR/rdonlyres/15410065-DF7C-44D2-92D8-DF58991E1640/0/Sustainability_Folio_040811.pdf; see page 3) produced during pavement rehabilitation.

  o Cold-in-place recycling reuses existing asphalt pavements to reduce material transport costs and reduce energy and emissions.

- Recycle materials to reduce waste:

  o WSDOT Standard Specifications (http://www.wsdot.wa.gov/publications/manuals/fulltext/M41-10/2014Amended4-7-2014.pdf) allow the use of hot-mix asphalt, recycled asphalt shingles, concrete rubble, recycled glass, steel furnace slag or aggregate to reduce the amount of materials entering the landfill.

  o Safely compost plant and animal waste to reduce energy from moving materials off-site and to avoid nuisance issues with carcass burials (http://www.wsdot.wa.gov/Environment/Biology/FAQwildlifeCollisions.htm#carcasses).

Air Quality

Tim Sexton
Air Quality, Noise and Energy
206-440-4549, SextonT@wsdot.wa.gov

Focus areas
- Greenhouse gas inventory and reduction strategies.

Priority actions in the 2013-2015 biennium
- Prepare agency greenhouse gas emissions inventory in summer 2014 and submit final report to the Department of Ecology in fall 2014, per RCW 70.235.050 (http://apps.leg.wa.gov/rcw/default.aspx?cite=70.235.050).

- Submit update of *WSDOT Strategy for Reducing Greenhouse Gas Emissions* (http://www.wsdot.wa.gov/NR/rdonlyres/1CE39C68-9FBB-4A47-B888-FE7F0F13E0B0/0/wsdot_ghg_strategy_Final.pdf) to the Department of Ecology in fall 2014, per RCW 70.235.050.

Current efforts
- Inventory and reduce WSDOT GHG emissions:

  o WSDOT completed the first agency GHG emissions inventory in 2009 and updated it in 2011 and 2012 to comply with RCW 70.235.050.

  o *WSDOT Strategy for Reducing Greenhouse Gas Emissions* tracks WSDOT GHG emissions reduction efforts and progress.

Related Research and Resources

System Efficiency

Multiple Strategies

Near-Term Transportation Energy and Climate Change Strategies: Interregional Transportation Related Greenhouse Gas Emissions Reduction Strategies, Transportation Sustainability Research Center, December 2013.
http://tsrc.berkeley.edu/sites/tsrc.berkeley.edu/files/Interregional%20GHG%20Final%20Report.pdf
This report reviews strategies for Caltrans for improving efficiency and lowering vehicle miles traveled to reduce GHG emissions from interregional travel. Appendix B includes a literature review on the effects of improving operational efficiency. The current preliminary investigation includes summaries of most of this literature.

Reference Sourcebook for Reducing Greenhouse Gas Emissions from Transportation Sources, FHWA, 2012.
http://www.planning.dot.gov/FHWA_tool/reference_sourcebook.pdf
This report on GHG mitigation strategies includes a comprehensive literature review of the effects of these strategies on GHG emissions. Key sections of the report are summarized below. (The author-date citations in the original report are included for reference.)

Land Use

From page 25:

> Recent research suggests that changing land use patterns may indeed be a key element in reducing GHG emissions in transportation. Estimates have been made that doubling residential density across a region could reduce VMT by about 5 to 12 percent (Committee for the Study on the Relationships Among Development Patterns, Vehicle Miles Traveled, and Energy Consumption, 2009). A recent report examined the potential impact of land use strategies on CO_2 emissions found that, by shifting 60 percent of new residential growth across the United States to compact patterns, CO_2 emissions could decline by 7 to 10 percent from current trends by 2050, or 79 million $MTCO_2$ annually (Ewing et al., 2008).

See page 29 of the report for references.

Transportation Demand Management

Road Pricing/HOT Lanes

GHG effects vary depending on the form of road pricing employed and the extent of the charges. Where road pricing has been employed in practice, before-and-after studies have found that VMT was reduced by between 2 and 10 percent, and where measured, GHGs declined by 2 to 6 percent. Some modeling-based studies have found much higher reductions, but only with very high per-mile charges that are well above the range of pricing that is normally considered in planning studies.

- In 2003, London implemented a £5 congestion charge to enter the central city during weekday business hours. This led to an estimated reduction of 19 percent of CO_2

emissions, with an additional decrease of 5 percent when the fee was raised to £8 in 2005. When the charging zone was further extended westward in 2007, the reduction in CO_2 was estimated at 6.5 percent (Transport for London, 2004, 2006, 2008).

- In 2006, Stockholm conducted a seven-month trial of a cordon system that charged between 10 and 20 kroner ($1.46 to $2.95 in 2009 USD), depending on the time of day. Emissions fell by 41,000 $MTCO_2$ per year, or 2.7 percent, across greater Stockholm (City of Stockholm, 2006). A later analysis, based on data from when the congestion charging system was reimplemented beginning in 2007, found that emissions again decreased by 2.7 percent, or 42,500 $MTCO_2$, per year in Stockholm County (Eliasson, 2009).

- In 1999, per capita emissions from road transportation in Singapore were 0.89 $MTCO_2$ while they were 5.37 $MTCO_2$ in the United States, in part because of Singapore's use of road pricing (Ang and Tan, 2001).

- A 2005 study of Leeds, UK, estimated that without road pricing, emissions would increase by 20 percent from 2005 to 2015. The study analyzed a variety of road pricing mechanisms, and concluded that a 2-pence-per-kilometer charge (6.5 cents per mile in 2009 USD) would reduce CO_2 by about 12 percent and was likely the best option (Mitchell et al., 2005, p. 6238).

- A Cophenhagen study modeled four road-pricing systems, concluding that they would reduce CO_2 emissions by 1 to 3 percent (Rich and Nielson, 2008).

- A study modeling tolls for various English cities found reductions in CO_2 emissions of 1.4 to 14.2 percent, with most in the range of 2 to 4 percent (Santos et al., 2000).

- A study of the San Francisco Bay Area's proposed regional HOT lane network estimated it would result in 7 percent lower CO_2 emissions during the morning peak hours than an HOV lane network in the same corridors (Metropolitan Transportation Commission, 2008).

See page 43 of the report for references.

Parking Management and Pricing

There is substantial evidence from empirical studies of U.S. parking scenarios that charging for parking reduces single-occupancy vehicle (SOV) trips by 7 to 15 percent (Vaca et al., 2005). In addition, parking fees instituted in Perth, Australia, in 1991 contributed to an estimated annual reduction of 1.7 million gallons of gasoline and 17,000 $MTCO_2$ (Sinclair Knight Merz, 2007).

See page 51 of the report for references.

Car Sharing

Studies in the United States and Canada have found that emissions declined on average by between 0.8 and 1.2 $MTCO_2$ annually per car sharing member, even after accounting for those members who drive more often because they did not previously own vehicles.

- In a recent study based on survey responses from over 6,200 car sharing members in North America, Martin and Shaheen (2010) found that on average, a household reduces its GHG by 0.84 $MTCO_2$ per year after joining car sharing. The authors concluded that the annual aggregate impact of car sharing reduces emissions by between 160,000 and 225,000 $MTCO_2$ per year.

- A study found that car sharing in Quebec reduced emissions by 1.2 $MTCO_2$ per member per year. (Communauto, Conseil Regional de l'environnement de Montreal, and Equiterre, 2007).

- Ryden and Morin (2005) claimed that in Europe, car sharing reduces members' CO_2 emissions by 40 to 50 percent. Specifically, two estimates from European programs found decreases in GHG emissions per member of 54 percent (Bremen, Germany) and 39 percent (Belgium).

- One review of four U.S. car sharing programs found that average per-member VMT decreases ranged from 7 to 43 percent. A San Francisco study found second-year average VMT reductions of 1.5 to 2.8 VMT per weekday, and an Arlington (Virginia) study found average VMT decreases of 43 percent (Millard-Ball et al., 2005).

- In a study of nine European programs, average VMT fell between 26 and 72 percent (Millard-Ball et al., 2005).

See page 59 of the report for references.

HOV/Ridesharing

Emissions benefits vary widely depending on policy and context, and generalizations cannot be made.

- An integrated ridesharing program in metropolitan Washington, D.C., reduced vehicle trips by 5,600 and reduced 146,000 VMT per day (LDA Consulting et al., 2005). Assuming an average fleet fuel economy of 20.7 mpg, this means a reduction of 62 $MTCO_2$ per day. The FY 2008 overall evaluation for all D.C.-area commuter programs combined found an aggregate reduction of 264,500 $MTCO_2$ per year (NCRTPB, 2009).

- In Atlanta, an evaluation of carpooling and ridesharing found a total daily trip reduction of 8,170 and net daily VMT reductions of 218,000 (CTE, 2002), contributing to an estimated daily reduction in emissions of 380 $MTCO_2$.

- The state of Washington has estimated that its commute trip reduction program, which included a variety of TDM initiatives, reduces VMT by 170 million per year, or 680,800 per day, and emissions by 85,700 MTCO2 per year, or 342 $MTCO_2$ per day (CTR Interim Report to the State Legislature, 2007).

- In a study of casual carpooling, the two existing casual carpool systems in the San Francisco Bay Area and northern Virginia—which account for an estimated 3,000 and 3,500 carpools per weekday—were found to save about 3 million gallons of gasoline per year (Dorinson et al., 2009), amounting to approximately 460 $MTCO_2$.

- For HOV lanes, older studies (from the 1970s) estimated reductions in fuel consumption ranging from 7 to 10 percent to up to 26 percent (Turnbull et al., 2006).

- A modeled study of returning HOV lanes to general-purpose lanes in Minneapolis found a savings in fuel consumption of 4,000 gallons per day because of increased speeds throughout the region (Cambridge Systematics and URS, 2002).

- A recent overview of the literature on HOV lanes and emissions concluded that there is a "lack of in-depth information on the air quality, energy and other related environmental impacts of HOV facilities" (Turnbull et al., 2006).

See page 77 of the report for references.

Transportation System Management Strategies

Traffic Signal Optimization

Where traffic signal optimization has been implemented and studied, the literature shows 3 to 12 percent fuel savings and GHG emissions at signalized intersections.

- A study in Toronto found that traffic signal optimization reduced fuel consumption by 4 to 7 percent and reduced emissions of all vehicle pollutants (including CO_2) by 3 to 6 percent per intersection within the study area (Greenough and Kelman, 1999).

- A Parisian study (Midenet et al., 2004) found that the adaptive real-time signal control system CRONOS led to a 3 to 4 percent reduction in GHG emissions at the site of each intersection. Researchers determined that signalization reduced an average of 8.8 lbs and 17.6 lbs of CO_2 per intersection per hour during off-peak and peak hours, respectively.

- In 1983, 41 California cities retimed 1,535 signals, leading in the first year to a reduction of 6.4 million gallons of fuel (California Energy Commission, 1984) and 56,898 metric tons of CO_2. Over the next 11 years, 160 California cities and counties retimed 12,245 signals in 334 projects, reducing fuel consumption by 8 percent (Berkeley, 1994).

- As part of the Clinton Climate Initiative (2009), the City of Portland optimized traffic signal timing at 135 intersections on 16 city streets. This optimization work has saved motorists over 1,750,000 gallons of gas each year. This reduction in gasoline consumption is equivalent to 15,460 MTCO$_2$ annually and 115 MTCO$_2$ per year per intersection.

- California's Fuel Efficient Traffic Signal Management (FETSIM) program optimized 3,172 traffic signals through 1998, and reported an average reduction in fuel use at these intersections of 8.6 percent for the program (Skabardonis, 2001).

- A project that optimized 700 signals in Northern Virginia resulted in a reduction in fuel use of 10 to 12 percent for those intersections (White et al., 2000).

- A study of signal optimization of 223 signals along seven corridors in Nashville, TN, found a fuel consumption reduction of nearly 6 percent along the seven corridors (Kimley-Horn and Associates, 2006).

See page 113 of the report for references.

Ramp Metering

The benefits from ramp metering to reduce GHG emissions are uncertain. Some studies report decreases in CO_2 emissions, primarily from smoother traffic, while others report increases, in part because of idling at meters.

- A study of the Twin Cities region in Minnesota found that ramp metering improved traffic volume, travel time, travel time reliability, safety and particulate emissions on highways. However, it worsened annual fuel consumption by 5.5 million gallons of fuel and produced approximately an additional 50,000 metric tons of CO_2 (Cambridge Systematics, 2001). This increase was due to the increased speeds on highways and the time vehicles spent idling at ramp meters. The change to vehicles' speed profiles resulted in a net decrease in the emission of hydrocarbons and carbon monoxide while elevating the emission of NOx and increasing overall fuel consumption.

- An evaluation of 16 fixed-time ramp meters installed in Portland, OR, in 1981 led to estimates that fuel consumption during the afternoon peak period, including the additional consumption caused by ramp delay, was reduced by almost 450 gallons of gasoline per weekday (Piotrowicz and Robinson, 1995; Oregon DOT, 1982), translating to approximately 4 metric tons of CO_2 reduced daily, and 1,000 metric tons reduced annually from workdays alone.

- One study simulated different ramp control algorithms for a 26-km (16.2-mile) stretch of freeway in Munich, Germany. It found that all control algorithms reduced fuel consumption by an average of 25 percent (Bogenberger et al., 2001).

See page 122 of the report for references.

Incident Management

Studies of individual urban incident management programs across the United States show varying impacts on GHG emissions, with calculated reductions ranging from 2 to 23 MTCO$_2$ per incident (compared to situations with no incident management).

- The Maryland CHART incident management program was estimated to save 4.84 million gallons of fuel on 20,515 incident clearances in 2005 (NTIMC, 2006). This amounts to approximately 235 gallons of fuel and 2 metric tons of CO_2 saved per incident.

- Florida's Road Ranger program is estimated to save 1.7 million gallons of fuel per month (Florida DOT, 2005; NTIMC, 2006), or 20.4 million gallons and 0.18 million metric tons of CO_2 per year. The program is estimated to save about 707 gallons of fuel and 6.3 metric tons of CO_2 per incident.

- Other studies have shown much higher fuel savings per incident. For example, an analysis of the San Antonio TransGuide System estimated 2,600 gallons of fuel—or 23 metric tons of CO_2—saved per major incident (Henk et al., 1997).

See page 130 of the report for references.

Roundabouts

Substituting a roundabout for a conventional signalized or signed intersection may reduce fuel consumption and CO_2 emissions by vehicles traversing that roundabout. Estimates suggest reductions of 16 to 30 percent in fuel consumption and fewer emissions at roundabouts than conventional intersections. However, the net GHG effect of replacing intersections with roundabouts remains largely unknown because fuel-efficiency benefits may be reduced or negated by emissions from roundabout construction.

- A study in Northern Virginia examined 10 signalized intersections and estimated the effects on traffic delay and safety if these intersections had been constructed as roundabouts. Annual fuel savings were estimated to be more than 200,000 gallons in total from the 10 roundabouts (20,000 gallons per roundabout per year on average, equivalent to 177 metric tons of CO_2).

- A project in Bern, Switzerland (population of 1 million) replaced the two most heavily traveled signalized intersections with roundabouts. The new roundabouts saw fuel savings and GHG emission reductions of about 17 percent as compared to the conditions at the site of the intersection that was replaced (European Academy of the Urban Environment, 2001).

- In a study of six intersections (five in Kansas and one in Nevada) where roundabouts replaced signalized intersections, the average hourly CO_2 emissions were reduced by 16 percent in peak morning hours and 59 percent in evening hours (Mandavilli et al., 2008).

- One study examined the effects of replacing a signalized intersection with a roundabout in Vaxjo, Sweden. A "car-following" method was used to directly observe and measure speed and acceleration before and after the roundabout was installed. The study found that fuel consumption declined by 28 percent (Várhelyi, 2002).

- Niittymaki and Hoglund (1999) compared fuel consumption between roundabouts and signalized intersections in Finland and found a reduction of 30 percent in fuel consumption for roundabouts at the intersection.

See page 146 of the report for references.

Resurfacing Roads

Road resurfacing may not significantly decrease and may even increase GHG emissions because the process of resurfacing roads may produce significant CO_2, possibly more than the amount saved by the resulting smooth roads.

Several studies have examined the fuel economy differences between rough and smooth roads. These studies indicate fuel economy differences (and consequently GHG differences) between 1 and 10 percent, depending on the type of vehicle and the roughness of the roads considered.

- Studies have shown that reducing highway surface roughness through improved maintenance and using less flexible pavement surfaces such as concrete rather than asphalt can reduce fuel consumption by as much as 10 percent for heavy trucks, and by a smaller amount for lighter vehicles (BTE, 1996; TOI, 2009).

- In a Missouri study of vehicle performance on roads before and after paving, diesel dump trucks averaged 5.97 miles per gallon before repaving; after paving they averaged 6.11 miles per gallon. This 0.14 mpg difference is approximately a 2.4 percent improvement.

- In one French study, researchers calculated that road surface characteristics can affect the fuel consumption of passenger cars by up to 7 percent (Du Plessis et al., 1990).

- Another French study found that fuel economy decreased from 34 miles per gallon to 32 miles per gallon (a decrease of approximately 6 percent) between the smooth and rough roads (Laganier and Lucas, 1990).

See page 159 of the report for references.

Quantifying Greenhouse Gas Mitigation Measures, California Air Pollution Control Officers Association, August 2010.
http://www.capcoa.org/wp-content/uploads/2010/11/CAPCOA-Quantification-Report-9-14-Final.pdf
This report quantifies the effectiveness of project-level mitigation of greenhouse gas emissions associated with land use, transportation, energy use, and other areas. Reductions of both overall vehicle miles traveled and emissions (unless otherwise noted) for transportation-related strategies include:

- Land Use/Location
  - Increase Density: 0.8 – 30.0%.

- o Increase Location Efficiency: 10 – 65%.
  - o Increase Diversity of Urban and Suburban Developments (Mixed Use) (including orienting a project toward a non-auto corridor): 9-30%.
  - o Increase Destination Accessibility (including locating a project near bike lanes or paths): 6.7 – 20%.
  - o Increase Transit Accessibility: 0.5 – 24.6%.
  - o Integrate Affordable and Below Market Rate Housing: 0.04 – 1.20%.
  - o Improve Design of Development (including incorporating bike lane street design, providing bike parking in non-residential projects, providing bike parking with multi-unit residential projects, dedicated land for bike trails, bike sharing programs): 3.0 – 21.3%.
- Neighborhood/Site Enhancements
  - o Provide Pedestrian Network Improvements (including creating urban non-motorized zones): 0 - 2%.
  - o Provide Traffic Calming Measures: 0.25 – 1.00%.
  - o Implement a Neighborhood Electric Vehicle (NEV) Network (including providing electric vehicle parking): 0.5-12.7% vehicle miles traveled (VMT) reduction since Neighborhood Electric Vehicles (NEVs) would result in a mode shift and therefore reduce the traditional vehicle VMT and GHG emissions. Range depends on the available NEV network and support facilities, NEV ownership levels, and the degree of shift from traditional.
- Parking Policy/Pricing
  - o Limit Parking Supply: – 12.5%.
  - o Unbundle Parking Costs from Property Cost: 2.6 – 13%.
  - o Implement Market Price Public Parking (On-Street): 2.8 – 5.5%.
  - o Require Residential Area Parking Permits: included in the previous three strategies.
- Commute Trip Reduction Programs
  - o Implement Commute Trip Reduction Program – Voluntary (including providing end of trip facilities and implementing a preferential parking permit program): 1.0 – 6.2% for commute vehicle miles traveled and commute trip GHG emissions.
  - o Implement Commute Trip Reduction Program - Required Implementation/Monitoring: 4.2 – 21.0% for commute vehicle miles traveled and commute trip GHG emissions.
  - o Provide Ride-Sharing Programs (including providing end of trip facilities and implementing a preferential parking permit program): 1 – 15% for commute vehicle miles traveled and commute trip GHG emissions.
  - o Implement Subsidized or Discounted Transit Program: 0.3 – 20.0% for commute vehicle miles traveled and commute trip GHG emissions.
  - o Encourage Telecommuting and Alternative Work Schedules: 0.07 – 5.50% for commute vehicle miles traveled and commute trip GHG emissions.
  - o Implement Commute Trip Reduction Marketing: 0.8 – 4.0% for commute vehicle miles traveled and commute trip GHG emissions.
  - o Implement Car-Sharing Program: 0.4 – 0.7%.
  - o Implement a School Pool Program: 7.2 – 15.8% for school vehicle miles traveled and school trip GHG emissions.
  - o Provide Employer-Sponsored Vanpool/Shuttle: 0.3 – 13.4% for commute vehicle miles traveled and commute trip GHG emissions.
  - o Implement School Bus Program: 38 – 63% for school vehicle miles traveled and school trip GHG emissions.
  - o Price Workplace Parking: 0.1 – 19.7% for commute vehicle miles traveled and commute trip GHG emissions.

- Implement Employee Parking "Cash-Out": 0.6 – 7.7% for commute vehicle miles traveled and commute trip GHG emissions.
- Road Pricing/Management
  - Implement Area or Cordon Pricing: 7.9 – 22.0%.
  - Improve Traffic Flow: 0 - 45%.
  - Required Project Contributions to Transportation Infrastructure Improvement Projects: grouped under trip reduction programs, above, as well as improving traffic flow.
  - Install Park-and-Ride Lots: Grouped under transit system improvements, area or cordon pricing, ride sharing programs, and employee sponsored pools.

See pages 281-297 for the effectiveness of transit system improvements and, pages 311-342 for the effectiveness of vehicle improvement strategies.

Transportation's Role in Reducing U.S. Greenhouse Gas Emissions, U.S. Department of Transportation, April 2010.
http://ntl.bts.gov/lib/32000/32700/32779/DOT_Climate_Change_Report_-_April_2010_-_Volume_1_and_2.pdf
See Section 3.5 for estimates of the emissions impacts of improving transportation system efficiency: "The collective impact of these strategies is relatively modest compared to vehicle and fuel technology strategies—approximately a 3 to 6 percent reduction relative to baseline 2030 transportation emissions" (p. 3-12). Highway traffic management strategies and real-time traveler information, including signal timing, freeway ramp metering, faster clearance of incidents, and variable message signs, have modest potential for reducing GHG emissions (where a modest reduction is less than 0.5 percent of total transportation emissions).

Reducing Greenhouse Emissions and Fuel Consumption: Sustainable Approaches for Surface Transportation, UCLA–Berkeley, March 2007.
http://tsrc.berkeley.edu/sites/tsrc.berkeley.edu/files/Reducing%20Greenhouse%20Emissions%20and%20Fuel%20Consumption.pdf
See Table 3 on page 14 for a summary of the energy and CO_2 reduction benefits of various ITS strategies, including:

- Traffic signal control: 1.6 to 50 percent in fuel savings and 4 percent in CO_2 emissions.

- Ramp metering: An unspecified reduction in freeway fuel consumption, but there do not seem to be overall emissions benefits because of idling at on-ramps.

- Incident management: Model calculations for a Maryland initiative showed a fuel savings of 5.06 million gallons per year.

Land Use

Driving and the Built Environment: The Effects of Compact Development on Motorized Travel, Energy Use, and CO_2 Emissions, Transportation Research Board, TRB Special Report 298, 2009.
http://onlinepubs.trb.org/Onlinepubs/sr/sr298.pdf
This report includes estimates of the emissions reduction benefits of smarter land use:

In an upper-bound scenario that represents a significant departure from current conditions, the committee estimates that steering 75 percent of new and replacement housing units into more compact development and assuming that residents of compact communities will

drive 25 percent less would reduce VMT and associated fuel use and CO_2 emissions of new and existing households by about 7 to 8 percent relative to base case conditions by 2030, with the gap widening to between 8 and 11 percent less by 2050. A more moderate scenario, which assumes that 25 percent of new and replacement housing units will be built in more compact developments and that residents of those developments will drive 12 percent less, would result in reductions in fuel use and CO_2 emissions of about 1 percent relative to base case conditions in 2030, growing to between 1.3 and 1.7 percent less than the base case in 2050. If the residents of compact developments drive only 5 percent less—the lower bound of available estimates—the savings in fuel use and CO_2 emissions would be less than 1 percent compared with the base case, even in 2050. Thus, the committee believes that reductions in VMT, energy use, and CO_2 emissions resulting from compact, mixed-use development would be in the range of less than 1 percent to 11 percent by 2050, although the committee disagreed about whether the changes in development patterns and public policies necessary to achieve the high end of these findings are plausible.

Growing Cooler: The Evidence on Urban Development and Climate Change, Urban Land Institute, 2007.
http://postcarboncities.net/files/SGA_GrowingCooler9-18-07small.pdf
According to this report:

> Making reasonable assumptions about growth rates, the market share of compact development, and the relationship between CO_2 reduction and VMT reduction, smart growth could, by itself, reduce total transportation-related CO_2 emissions from current trends by 7 to 10 percent as of 2050. This reduction is achievable with land-use changes alone.

Integrated Corridor Management

"Integrated Corridor Management Using ITS—Analysis, Modeling and Simulation," Cambridge Systematics Inc., *8th European Congress and Exhibition on Intelligent Transport Systems and Services,* 2011.
http://www.camsys.com/pubs/ICM_ITS_AMS_APR11.pdf
This study estimated annual fuel and emissions savings for San Diego, Dallas and Minneapolis ICM projects. The report predicted annual fuel savings of 323,000 gallons (San Diego), 981,000 gallons (Dallas), and 17,600 gallons (Minneapolis). This would correlate to approximately 6 million, 17.6 million, and 316,800 lbs of annual CO_2 reductions for the three sites, respectively. The report also estimated annual mobile emissions reductions of 3,100 tons (San Diego), 9,400 tons (Dallas), and 175 tons (Minneapolis).

"Integrated Corridor Management," *Public Roads*, Vol. 74, No. 3, 2010.
http://www.fhwa.dot.gov/publications/publicroads/10novdec/02.cfm
There are several ICM corridors located throughout the United States that are currently in the preliminary testing phase. The United States Department of Transportation anticipates that independent evaluations of all of the ICM demonstration sites will be developed by the end of 2014 to determine whether or not ICM strategies deliver the expected benefits. Currently, ICM research involving analysis, modeling and simulation on several test corridors (San Francisco, Dallas, Minneapolis and San Diego) indicate that corridors that implement ICM can expect greater travel time reliability and productivity of corridor networks, and reduced fuel consumption and emissions.

Transportation Demand Management (General)

Active Travel Co-Benefits of Travel Demand Management Policies That Reduce Greenhouse Gas Emissions, Mineta Transportation Institute, April 2014.
http://transweb.sjsu.edu/PDFs/research/1109-active-travel-greenhouse-gas-reduction.pdf
From the Abstract: The results of this study suggest that distance-based vehicle pricing may increase walking by about 10 percent and biking by about 17 percent, and concurrently greenhouse gas emissions (GHG) from vehicle miles of travel (VMT) may be reduced by about 16 percent. Transit expansion and supportive development patterns may increase active travel by about 2 to 3 percent for both walk and bike modes while also reducing VMT by about 4 percent on average. The combination of all three policies may increase time spent walking by about 13 percent and biking by about 19 percent, and reduce VMT by about 19 percent.

"Reducing Local Traffic Emissions at Urban Intersection Using ITS Countermeasures,"
IET Intelligent Transport Systems, Volume 7, Issue 1, 2013: 78-86.
Abstract at http://trid.trb.org/view/2013/C/1252790
Traffic emissions have significantly increased during the last two decades in many countries because of the increased number of vehicles. Traffic emissions have become the main source of air pollution in urban areas, where breaches of the EU limit values frequently occur. To reduce these emissions, local traffic measures can be implemented complementary to regional and national measures. In this study, the impact of various traffic measures at a single intersection is investigated using a traffic model and an emission model. The measures included are traffic demand control, banning heavy duty vehicles (HDVs) and speed restriction. It was found that reducing traffic demand by 20 percent led to about 23 percent reduction in terms of CO_2, NOx and PM10 emissions. Banning HDVs led to a significant reduction of NOx and PM10 emissions. Although speed restriction reduced both CO_2 and NOx emissions by 16.1 and 13.4 percent, PM10 emissions increased by 19 percent, mainly from HDVs.

Potential Changes in Emissions Due to Improvements in Travel Efficiency—Final Report, 2011.
http://epa.gov/otaq/stateresources/policy/420r11003.pdf
This EPA report uses the MOVES2010 emissions model and metropolitan travel data to estimate potential national emissions reductions from transportation control measures. See page vii for a chart summarizing estimated emissions reductions for various strategies:

Resulting Emissions Reductions for Selected Pollutants								
Scenario	Percent Emissions Reduction							
	2030				2050			
	CO_2 equivalent*	$PM_{2.5}$	NO_x	VOC	CO_2 equivalent*	$PM_{2.5}$	NO_x	VOC
1- Region-wide TDM	0.10%	0.10%	0.10%	0.09%	0.26%	0.26%	0.26%	0.25%
2 - TDM + land use changes	1.01%	1.01%	1.00%	0.98%	2.97%	2.96%	2.93%	2.86%
3 - TDM + land use changes + transit fare reduction	1.40%	1.40%	1.39%	1.36%	4.19%	4.18%	4.16%	4.08%
4 - TDM + land use changes + transit fare reduction + transit service improvements	1.44%	1.44%	1.43%	1.41%	4.30%	4.29%	4.28%	4.23%
5 - TDM + land use changes + transit fare reduction + transit service improvements + parking fees	2.92%	2.92%	2.91%	2.90%	6.98%	6.94%	6.87%	6.68%
6 - TDM + land use changes + transit fare reduction + transit service improvements + mileage fees	1.94%	1.93%	1.92%	1.87%	6.28%	6.25%	6.17%	5.95%
7 - TDM + land use changes + transit fare reduction + transit service improvements + parking fees + mileage fees	3.42%	3.42%	3.40%	3.35%	8.83%	8.78%	8.65%	8.29%

* CO_2 equivalent = $[CO_2 + 21*(CH_4) + 310*(N_2)]$

HOV, Managed Lanes and Ridesharing

"Are HOV/Eco-Lanes a Sustainable Option to Reducing Emissions in a Medium-Sized European City?" *Transportation Research Part A: Policy and Practice*, Volume 63, pages 93-106, 2014.
Abstract at http://www.sciencedirect.com/science/article/pii/S0965856414000597
This study models the emissions impacts of HOV and eco-lanes in medium European cities, and finds a reduction in CO_2 of 37 percent.

"Greenhouse Gas Emission Impacts of Carsharing in North America," *IEEE Transactions on Intelligent Transportation Systems*, Volume 12, Issue 4, pages 1074-1086, 2011.
Abstract at http://trid.trb.org/view/2011/C/1123329
Abstract: This paper evaluates the greenhouse gas (GHG) emission impacts that result from individuals participating in carsharing organizations within North America. The authors conducted an online survey with members of major carsharing organizations and evaluated the change in annual household emissions (e.g., impact) of respondents that joined carsharing. The results show that a majority of households joining carsharing are increasing their emissions by gaining access to automobiles. However, individually, these increases are small. In contrast, the remaining households are decreasing their emissions by shedding vehicles and driving less. The collective emission reductions outweigh the collective emission increases, which implies that carsharing reduces GHG emissions as a whole. The results are reported in the form of an observed impact, which strictly evaluates the changes in emissions that physically occur, and a

full impact, which also considers emissions that would have happened but were avoided due to carsharing. The mean observed impact is –0.58 t GHG/year per household, whereas the mean full impact is –0.84 t GHG/year per household. Both means are statistically significant. We present a sensitivity analysis to evaluate the robustness of the results and find that the overall results hold across a variety of assumptions. The average observed vehicle kilometers traveled (VKT) per year was found to decline by 27 percent. We conclude with an evaluation of the annual aggregate impacts of carsharing based on current knowledge of the industry membership population.

"Estimating the Energy Consumption Impact of Casual Carpooling," *Energies*, Volume 4, No. 1, pages 126-139, 2011.
http://www.flexiblecarpooling.org/casualcarpoolingenergysaving.pdf
This New Zealand report estimates that casual carpooling in San Francisco conserves between 1.7 and 3.5 million liters of gasoline per year. This is equivalent to 0.45 to 0.92 million gallons of gasoline saved annually, with emission reductions ranging between 4,000 and 8,335 $MTCO_2$.

Flexible Carpooling: Exploratory Study, Institute of Transportation Studies, University of California at Davis, 2009.
http://eec.ucdavis.edu/files/2009flexiblecarpoolstudy.pdf
This study found that casual carpool systems in the San Francisco Bay Area and in northern Virginia— systems that account for 3,000 and 3,500 carpools per day, respectively—save nearly 3 million gallons of gasoline per year and reduce emissions by approximately 27,000 metric tons of CO_2. The report estimated that a group of 150 commuters who switched from SOV commuting to casual carpooling would save almost 52,000 gallons of gasoline per year. This data was based on assumptions of 12-mile commutes, and HOV lanes that had smoother-flowing traffic at higher speeds than the conventional general-purpose lanes.

Twin Cities HOV Study, Volume I, Minnesota Department of Transportation, 2002.
http://www.dot.state.mn.us/information/hov/pdfs/full_study.pdf
This study modeled the conversion of existing HOV lanes back to general-purpose lanes in the city of Minneapolis, and found a savings of 4,000 gallons of fuel per day due to an increase of average speeds throughout the region. This could correlate to an emissions reduction of approximately 36.2 metric tons CO_2.

"Fuel Saving and Ridesharing in the US: Motivations, Limitations, and Opportunities," *Transportation Research Part D: Transport and Environment,* Volume 4, Issue 1, pages 14-21, 2009.
Abstract at http://www.sciencedirect.com/science/article/pii/S1361920908001168
This study explores the theoretical fuel savings from increased ridesharing in the United States concluded that if one additional occupant were added for every 100 vehicles on the road, 0.80 to 0.82 billion gallons of gasoline could be saved annually. If one additional passenger were added for every 10 vehicles on the roadway, the annual fuel savings would be 7.54 to 7.74 billion gallons, approximately 5.4 percent of the fuel consumed annually by cars and light trucks.

Traffic Signal Optimization

"Investigating Emission Reduction Benefit from Intersection Signal Optimization,"
Journal of Intelligent Transportation Systems, Volume 17, Issue 3, pages 200-209, 2013.
Abstract at http://www.tandfonline.com/doi/abs/10.1080/15472450.2012.716670#.U-gU5vlSYlQ

Abstract: Most existing intersection signals are timed based on delay minimization. However, minimizing delay does not necessarily lead to the minimization of emissions at an intersection. No study has focused on the difference or the trade-off between delay based and emissions based signal optimization. Delay-based optimization typically uses macroscopic flow conditions such as traffic demands, saturation flow rates, and average delay. However, the latest emission model, MOVES (Motor Vehicle Emission Simulation), requires second-by-second individual vehicle speed profiles, which makes the model difficult to formulate directly in an emission-based signal optimization problem. This study first develops a methodology to derive vehicle profiles given macroscopic inputs so that MOVES can be applied to estimating emissions. Then an optimization methodology of signal timing is developed and solved with a genetic algorithm. The objective function of the optimization problem considers both delay and emissions, with the signal timing elements being the decision variables. Through a case study, the air quality benefit by reducing vehicle emissions through intersection signal control is demonstrated, and the trade-off between operational and emission performance measures is investigated. Furthermore, the air quality benefit from intersection signal control is discussed under different scenarios of cycle lengths, percentages of turning vehicles, and traffic demands on major/minor roads.

"Evaluating the Impacts of Urban Corridor Traffic Signal Optimization on Vehicle Emissions and Fuel Consumption," *Transportation Planning and Technology*, Volume 35, Issue 2, pages 145-160, 2012.
Abstract at http://trid.trb.org/view/2012/C/1134534

Abstract: This study investigates the impacts of traffic signal timing optimization on vehicular fuel consumption and emissions at an urban corridor. The traffic signal optimization approach proposed integrates a TRANSIMS microscopic traffic simulator, the VT-Micro model (a microscopic emission and fuel consumption estimation model), and a genetic algorithm (GA)-based optimizer. An urban corridor consisting of four signalized intersections in Charlottesville, VA, USA, is used for a case study. The result of the case study is then compared with the best traffic signal timing plan generated by Synchro using the TRANSIMS microscopic traffic simulator. The proposed approach achieves much better performance than that of the best Synchro solution in terms of air quality, energy and mobility measures: 20 percent less network-wide fuel consumption, 8 to 20 percent less vehicle emissions, and nearly 27 percent less vehicle-hours-traveled (VHT).

"Effects of Traffic Signal Coordination on Noise and Air Pollutant Emissions,"
Environmental Modelling & Software, Volume 35, pages 74-83, 2012.
Abstract at http://www.sciencedirect.com/science/article/pii/S1364815212000576

From the Abstract: This paper reports on a computational study in which a microscopic traffic simulation model (Paramics) is combined with submodels for the emission of noise (Imagine) and air pollutants (VERSIT+). Through the simulation of a range of scenarios, the model is used to investigate the influence of traffic intensity, signal coordination schemes and signal parameters on the noise, carbon dioxide, nitrogen oxides and particulate matter emissions along an arterial road equipped with a series of traffic lights. It was found that the introduction of a green wave could potentially lower the emissions of the considered air pollutants by 10 to 40 percent in the most favorable conditions, depending on traffic flow and signal timing settings. Sound pressure levels were found to decrease by up to 1 dB(A) near the traffic signals, but to

increase by up to 1.5 dB(A) in between intersections. Traffic intensity and green split were found to have the largest influence on emissions, while the cycle time did not have a significant influence on emissions.

"Benefits of Traffic Light Synchronisation," *ITS International*, Volume 17, Issue 3, page 22, 2011.
Abstract at http://trid.trb.org/view/2011/C/1107680
Abstract: This article describes how the Alicia Parkway corridor, which is located in Orange County, California, was part of Phase 1 of an inter-jurisdictional Traffic Light Synchronization Program (TLSP) in the County that was designed to increase mobility and overall drive quality while reducing fuel consumption and greenhouse gas emissions. By increasing average speeds and reducing travel times via the reduction in stops, the program sought to reduce vehicle acceleration and deceleration events along the corridor and these have been identified as the leading cause in greenhouse gas production. The TLSP was funded through the Proposition 1B –Transportation Bond Program (Prop 1B) and for Alicia Parkway addresses the corridor's east-west segments on either side of Interstate 5 (I-5), the main north-south freeway. During the weekday, Alicia Parkway, a freeway-centric corridor, has traffic volumes in excess of 60,000 vehicles per day on its short spans near the I-5 freeway. After installing two Econolite Centracs Advanced Traffic Management System (ATMS) and several ASC/3 controllers, Alicia Parkway saw reductions in travel times (11 percent), number of stops (33.3 percent) and greenhouse gases (8,100+ lbs.). Moreover, the estimated three-year fuel savings are projected to exceed 1.1 million gallons (based on 250 weekdays per year).

"Assessment of the Impact of Speed Limit Reduction and Traffic Signal Coordination on Vehicle Emissions Using an Integrated Approach," *Transportation Research Part D: Transport and Environment*, Volume 16, Issue 7, pages 504-508, 2011.
Abstract at http://trid.trb.org/view/2011/C/1114592
Abstract: This paper examines the effects of two traffic management measures, speed limit reduction and coordinated traffic lights, in an area of Antwerp, Belgium. An integrated model is deployed that combines the microscopic traffic simulation model Paramics with the carbon dioxide (CO_2) and nitrogen oxide (NOx) emission model VERSIT+. On the one hand, reductions in CO_2 and NOx emissions of about 25 percent were found if speed limits are lowered from 50 to 30 km/h in the residential part of the case study area. On the other hand, reductions in the order of 10 percent can be expected from the implementation of a green wave signal coordination scheme along an urban arterial road.

Intelligent Transportation Systems Benefits, Costs, Deployment, and Lessons Learned: 2008 Update, U.S. Department of Transportation, 2008.
http://www.itscosts.its.dot.gov/its/benecost.nsf/images/Reports/$File/BCDLL-14412_full.pdf
Modeling studies of coordinated signal control in five U.S. localities found reductions in fuel use ranging from no significant change in Seattle to a 13 percent decline in Syracuse, NY.

Traffic Signal Timing Optimization Study for the Metro Nashville Signal System, Kimley-Horn and Associates, 2006.
http://www.nashville.gov/pw/pdfs/Signal_Optimization_FINAL_2006.pdf
This study of signal optimization in Nashville, TN, found that retiming 223 signals along seven traffic corridors resulted in fuel use reductions of nearly 6 percent.

"Signalized Intersection with Real-Time Adaptive Control: On-Field Assessment of CO_2 and Pollutant Emission Reduction," *Transportation Research Part D: Transport and the Environment*, Volume 9, Issue 1, pages 29-47, 2004.
Abstract at http://trid.trb.org/view/2004/C/686368
This study found that an intersection equipped with a real-time adaptive signal control system known as CRONOS led to a 3 to 4 percent reduction in GHG emissions. The CRONOS system is a real-time traffic control algorithm, developed in France in the late 1990s, that utilizes video-based measurements of queue lengths or spatial occupancy to coordinate traffic signals across multiple intersections. The study was performed over a period of 8 months at an intersection in the suburbs of Paris that experienced between 2,600 and 3,300 vehicles per hour. Utilizing video sensors to measure the speed and volume of local traffic going through the intersection, the study found that the CRONOS signalization decreased CO_2 emissions by an average of 8.8 lbs and 17.6 lbs (4 kg and 8 kg) per intersection per hour during off-peak and peak hours, respectively.

"Evaluation of Transit Signal Priority Benefits Along a Fixed-Time Signalized Arterial," *81st Annual Meeting of the Transportation Research Board*, Paper 02-2137, 2002.
Abstract at http://trid.trb.org/view.aspx?id=710242
Simulation of a transit signal priority system along a heavily traveled corridor in Arlington County, Virginia, found a 2 to 3 percent reduction in fuel consumed by buses across a number of priority scenarios.

"ITS Benefits: The Case of Traffic Signal Control Systems," *80th Annual Transportation Research Board Meeting,* Paper 01-3286, 2001.
Abstract at
http://www.itsbenefits.its.dot.gov/its/benecost.nsf/ID/42419C3E5993E9CD852569EA0071D556
This paper summarizes an evaluation of the benefits of optimizing traffic signal timing plans, coordinating traffic signal control, and implementing adaptive signal control at locations throughout the state of California. As part of the Fuel Efficient Traffic Signal Management (FETSIM) program, 41 California cities retimed 1,535 traffic signals in 1983. Because follow-up field studies reported reduced vehicular delays and fuel consumption, the signal timing program was expanded over the next 11 years to retime 12,245 traffic signals in 160 California cities and counties. Throughout these areas it was estimated that fuel use was decreased by approximately 8 percent. In 1983, the first year of the program, efficiency benefits resulted in a reduction of 6.4 million gallons of fuel, equating to 56,898 metric tons of CO_2 annually and 37 metric tons of CO_2 per year per intersection.

"Traffic Signal Coordination Across Jurisdictional Boundaries: Field Evaluation of Efficiency, Energy, Environmental, and Safety Impacts," *Transportation Research Record 1727*, pages 42-51, 2000.
Abstract at http://trb.metapress.com/content/80633j426j565218/
This study of coordinated traffic signals conducted within the Phoenix metropolitan area, along the Scottsdale Road–Rural Road corridor, found that fuel consumption was on average reduced by 1.6 percent over all of the measured intersections.

Traffic Signal Optimization for Tysons Corner Network Volume I: Evaluation and Summary, Virginia DOT, 2000.
Summary at
http://www.benefitcost.its.dot.gov/ITS/benecost.nsf/ID/5526CCA9B17F9309852569610051E2DA
This study found that a project in Northern Virginia that optimized 700 signals resulted in a reduction in fuel use between 10 and 12 percent.

Ramp Metering

"An Evaluation of the Ramp Metering Effectiveness in Reducing Carbon Dioxide Emissions," *Simulation: Transactions of the Society for Modeling and Simulation International*, Volume 88, No. 11, pages 1368-1378, 2012.
Abstract at http://sim.sagepub.com/content/88/11/1368
Using a simulation of a 10.15-km South Korean overpass with heavy congestion during peak hours, researchers estimated emissions before and after a locally controlled ramp metering device (allowing four vehicles every 30 seconds) was installed. The study showed that while the emissions of vehicles at on-ramps were increased, there was a 7.3 percent net reduction in overall CO_2 emissions. The reduction in CO_2 emissions amounted to 818.4 kg per hour, 3,273.6 kg per day, and 1,194.9 tons per year.

Optimize Pollutant Emissions Through Adaptive Highway Management, METRANS Transportation Center, 2011.
http://ntl.bts.gov/lib/42000/42500/42588/METRANS_10-25_Optimize_Pollutant_Emissions_through_Adaptive_Highway_Management.pdf
Abstract: In this project, we investigated the possibility to reduce greenhouse emission (mainly CO_2) from urban highways by adaptive ramp meter control. QUADSTONE PARAMICS software was used to build a microscopic traffic model for a 4-lane highway section containing on/off ramps. A mathematical model of CO_2 emission as a function of vehicle's speed and acceleration was also developed. Total emission of simulated highway section was calculated under on a variety of ramp meter control scenarios and traffic densities. It has been found that the emission rate of greenhouse gases varies non-linearly with vehicle's speed. While vehicles move at relatively high speed (i.e. greater than 50 mph), the emission rate increases monotonically with speed of vehicle. On the other hand, when vehicles move at extremely low speed (i.e. less than 20 mph), the emission rate is reversely proportional to vehicle's speed. In addition, vehicle's acceleration also plays an important role. This non-linear behavior of emission rate indicates the possibility to optimize greenhouse emission through smart speed and mobility control on urban corridors. A test model of a 1.5-mile 4-lane highway section with one on-ramp and one off-ramp was developed. A fixed time ramp meter is placed on the on-ramp and simulated the model at different scenarios by adjusting the red-time interval of the meter. It is observed that in light or moderate traffic scenarios, the optimal red time interval increases with traffic density. However, when the traffic becomes very heavy or jammed, the optimal red time actually decreases. Our simulation also shows the overall emission decreases with highway speed limit. The fact that the red time interval needs to be reduced under heavy traffic in order to reduce CO_2 emission indicates a trade-off between improving highway throughput and reducing CO_2 emission. Optimization plans solely targeting for higher throughput not necessarily leads to lower emission, on the contrary, it may increase the emission in some cases. It is also observed that implementing ramp meter control works better for heavy traffic situations than light traffic ones; while speed limit control works better for light traffic situations. This suggests implementing both active ramp meter control and active speed control could potentially minimize the average emission.

Northern San Joaquin Valley Regional Ramp Metering and High Occupancy Vehicle (HOV) Lane Master Plan, DKS Associates in association with PB Americas, 2008.
http://www.stancog.org/pdf/draft-final-report-ramp-metering-hov-master-plan.pdf
This study analyzed the potential traffic alleviation benefits of ramp metering in the San Joaquin valley. The report concluded through simulation that ramp metering would tend to increase mainline vehicle speeds by roughly 5 percent, and that overall there would be negligible fuel savings and GHG emissions reductions, finding only a 1 percent improvement.

"Evaluation of Ramp Meter Control Effectiveness in Two Twin Cities Freeways," *81st Annual Meeting of the Transportation Research Board,* 2002.
http://www.aimsun.com/papers/TRB2002_RAMP_Metering_Evaluation_v3.pdf
A simulation study of the Minneapolis-St. Paul system found 2 to 55 percent fuel savings at individual ramp metering locations along two corridors that were modeled under varying levels of travel demand.

"ACCEZZ—Adaptive Fuzzy Algorithms for Traffic Responsive and Coordinated Ramp Metering," *Applications of Advanced Technologies in Transportation,* pages 744-753, 2002. Abstract at http://cedb.asce.org/cgi/WWWdisplay.cgi?132366. A 2001 version of the paper is available at http://www.its.uci.edu/its/publications/papers/CTSS/UCI-ITS-TS-WP-01-7.pdf.

This study simulated different ramp control algorithms for a 16.2-mile stretch of freeway in Munich, Germany. It found that all control algorithms reduced fuel consumption by an average of 25 percent, accounting for improved mainline flow and higher accelerations at the on-ramps while also significantly lowering emissions of NOx, CO and hydrocarbon.

Twin Cities Ramp Meter Evaluation, Minnesota Department of Transportation, 2001.
http://www.dot.state.mn.us/rampmeter/pdf/finalreport.pdf
This study of the Twin Cities region in Minnesota concludes that ramp metering improved traffic volume, travel time, travel time reliability, safety, and particulate emissions on highways. However, it concludes that ramp metering resulted in higher annual fuel consumption from the higher vehicle speeds on highways and increased time idling at on-ramps. However, the report notes that it used a straight line estimation technique to calculate the increased fuel use, and explains that this model may not have adequately accounted for the tempering of flow typically brought about by ramp metering (which may reduce fuel consumption). The report did note that four other areas that instituted ramp metering systems estimated fuel savings ranging from 6 to 13 percent.

Incident Management

"Measuring Sustainability: How Traffic Incident Management Through Intelligent Transportation Systems has Greater Energy and Environmental Benefits than Common Construction-Phase Strategies for 'Green' Roadways," *International Journal of Sustainable Transportation*, Volume 6, Issue 1-6, pages 282-297, 2012.
Abstract at http://trid.trb.org/view/2012/C/1132978
This paper uses a life-cycle assessment simulation to compare the benefits of incident management systems to those of green construction practices, and estimates that incident management programs could save 51,000 gallons of gasoline annually, and subsequently 416 metric tons of CO_2.

Annual Report: Smart SunGuide TMC, Florida DOT, 2005
http://www.smartsunguide.com/PDF/Annual%20Report%2006_JAN_31%20FINAL.pdf
Florida's Road Ranger program, part of the SMART (Systems Management for Advanced Roadway Technologies) ITS deployments package, was estimated to save approximately 1.8 million gallons of gasoline and 14,000 metric tons of CO_2 emissions annually.

Performance Evaluation of CHART: An Incident Management Program, 2000.
http://ntl.bts.gov/lib/jpodocs/repts_te/13135
In this evaluation, the CHART (Coordinated Highways Action Response Team) incident management program is estimated to reduce total delay time from 32,814 traffic incidents by

29.98 million vehicle-hours, and reduce overall fuel consumption by 5.06 million gallons. This equates to approximately 154 gallons of fuel and 1.3 metric tons of CO_2 saved per incident.

Roundabouts

"Experimental Analysis of Single-Lane Roundabout Slip Lanes: Fuel Consumption and Emissions," *Second Conference on Green Streets, Highways, and Development,* pages 240-250, 2013.
Abstract at http://trid.trb.org/view/2013/C/1276768
Abstract: Vehicular fuel consumption and emissions performance (carbon dioxide (CO_2) and carbon monoxide (CO)) are examined experimentally within single-lane roundabouts with slip lane under yield, stop, and free-flow exit control scenarios; these are compared with no slip lane using a gap acceptance-based performance experimental assessment SIDRA tool. For comparison with other types of traffic control, the same experimental roundabout is converted into a signal intersection and into an all-way stop-controlled intersection. With a free-flow slip lane exit type, overall average total roundabout fuel consumption was reduced by 26 percent, CO_2 emissions were reduced 27 percent, and CO emissions were reduced 17 percent, compared with an all-way stop-controlled intersection. As expected, results indicate that a roundabout with a free-flow slip lane exit type significantly reduces total average fuel consumption and pollutant emissions within a roundabout compared with all-way stop-controlled intersection.

Continued Reliance on Traffic Signals: The Cost of Missed Opportunities to Improve Traffic Flow and Safety at Urban Intersections, Insurance Institute for Highway Safety, 2005.
Abstract at http://trid.trb.org/view/2005/M/771437
From the Abstract: The present study examined ten signalized intersections in Northern Virginia that were newly constructed or recently modified. Standard traffic engineering algorithms were used to estimate the effects on traffic delays and motor vehicle crashes if these intersections had been constructed as roundabouts. It was estimated that roundabouts would have reduced vehicle delays by 62 to 74 percent, depending on the intersection, thus eliminating more than 300,000 hours of vehicle delay on an annual basis. Annual fuel consumption would have been reduced by more than 200,000 gallons, with commensurate reductions in vehicle emissions.

"Impact of Modern Roundabouts on Vehicular Emissions," *Proceedings of the Mid-Continent Transportation Research Symposium,* 2003.
http://www.ctre.iastate.edu/pubs/midcon2003/MandavilliRoundabouts.pdf
This study investigated the effect on emissions of replacing six stop-controlled intersections with modern roundabouts. Reductions in carbon dioxide were between 16 and 59 percent, and there was a reduction of 20 to 48 percent for oxides of nitrogen. Emissions were estimated using modeling software and observed before-and-after data on traffic volumes and other factors.

Pavement Conditions

PCC Surface Characteristics, Transportation Pooled Fund 5(134), Minnesota Department of Transportation (lead agency), in progress; expected completion date December, 2014.
http://www.pooledfund.org/Details/Study/363
As part of TPF-5(134), MnDOT is conducting extensive rolling resistance testing at the MnROAD pavement research facility. This includes the published report, *Pavement Texture Evaluation and Relationships to Rolling Resistance at MnROAD* (http://www.lrrb.org/media/reports/201316.pdf), which investigates the relationship between rolling resistance and other pavement surface characteristics. This study uses data collected in a 2012 study, *Rolling Resistance Measurements at the MnROAD Facility* (http://www.mrr.dot.state.mn.us/research/pdf/201207.pdf), in cooperation with the University of Gdansk, Poland. In a follow-up study (report forthcoming by the end of 2014), MnDOT is conducting a second round of rolling resistance measurements at MnROAD for a large variety of pavement materials and surface types, and analyzing the relative energy consumption of each surface.

Verification of Pavement Structure and Deflection Effects on Vehicle Fuel Economy and GHG Emissions, Minnesota Department of Transportation, in progress; expected completion date October 31, 2014.
Abstract at http://trid.trb.org/view/2014/P/1310927
Abstract: The goals of this project are to first compare different pavement deflection energy dissipation models and the results they provide for estimated fuel consumption and greenhouse gas (GHG) emissions for a range of pavements, vehicles and climates using well characterized and documented sections, and then to verify the same models using the results of the field measurements on the same sections with instrumented vehicles following the general approach used by Michigan State for NCHRP 1-45. This work is part of the California Department of Transportation (Caltrans) participation in the Miriam (Models for rolling resistance In Road Infrastructure Asset Management systems) project which is being performed by a consortium of European national highway research laboratories and the Federal Highway Administration (FHWA). Caltrans has requested that the Minnesota Department of Transportation (MnDOT) provide an independent review of the evaluation, led by Dr. Lev Khazanovich.

Reducing Greenhouse Gas Emissions through Strategic Management of Highway Pavement Roughness, *Environmental Research Letters*, Vol. 9, March 2014.
http://iopscience.iop.org/1748-9326/9/3/034007/pdf/1748-9326_9_3_034007.pdf
From the abstract: This letter describes a life cycle approach to assess changes in total GHG (measured in CO_2-e) emissions from strategic management of highway pavement roughness. Roughness values for triggering treatments are developed to minimize GHG considering both treatment and use phase vehicle emission. With optimal triggering for GHG minimization, annualized reductions on the California state highway network over a 10-year analysis period are calculated to be 0.82, 0.57 and 1.38 million metric tons compared with historical trigger values, recently implemented values and no strategic intervention (reactive maintenance), respectively. Abatement costs calculated using $/metric-ton CO_2-e are higher than those reported for other transportation sector abatement measures, however, without considering all benefits associated with pavement smoothness, such as vehicle life and maintenance, or the time needed for deployment.

"Impact of Pavement Roughness on Vehicle Free-Flow Speed," T. Wang, J. Harvey, J. Lea and C. Kim, *Journal of Transportation Engineering*, 2014.
Abstract at http://ascelibrary.org/doi/abs/10.1061/%28ASCE%29TE.1943-5436.0000689
From the Abstract: The results showed that pavement roughness has a very small effect on free-flow speed within the range of this study. For the IRI coverage in this study (90 percent of the records have an IRI of 3 m/km or lower and 90 percent of the records have an IRI change of 2 m/km or lower), a change of IRI of 1 m/km (63 in./mi) results in a change of average free-flow speed of approximately 0.48–0.64 km/h (0.3–0.4 mph). This result indicated that making a rough segment of pavement smoother through application of a maintenance or rehabilitation treatment will not result in substantially faster vehicle operating speeds, and therefore the energy and emission reductions gained from the reduced rolling resistance will not be offset by increased fuel consumption from faster speeds. However, developing a good model to predict the free-flow speed was not fully successful. The southern California interstate freeway model yielded the best result with an adjusted R-squared of 0.72.

"Estimating Vehicle Operating Costs Due to Pavement Surface Conditions,"
Transportation Research Board 93rd Annual Meeting, Paper 14-5100, 2014.
http://docs.trb.org/prp/14-5100.pdf
This paper includes an assessment of the effects of pavement roughness on fuel consumption. From the abstract:

> An increase in IRI of 1 m/km (63.4 in/mile) increases fuel consumption of passenger cars by 2% to 3% irrespective of speed. For heavy trucks, this increase is 1% to 2% at highway speed (112 km/h or 70 mph) and 2% to 3% at low speed (56 km/h or 35 mph). Surface texture (MPD) and pavement type have no effect on fuel consumption for all vehicle classes except for heavy trucks. An increase in MPD of 1 mm (0.039 in.) increases fuel consumption by 1.5% at 88 km/h (56 mph) and 2% at 56 km/h (35 mph). The effect of pavement type on fuel consumption was statistically not significant for all light vehicles, and only statistically significant for heavy trucks at low speed in summer conditions. Heavy trucks driven on AC pavements consume 4% more fuel than on PCC pavements at 56 km/h (35 mph) at 30°C.

UCPRC Life Cycle Assessment Methodology and Initial Case Studies on Energy Consumption and GHG Emissions for Pavement Preservation Treatments with Different Rolling Resistance, University of California Pavement Research Center, 2012.
http://www.ucprc.ucdavis.edu/PDF/UCPRC-RR-2012-02.pdf
Abstract: This report describes a pavement life cycle assessment (LCA) model developed to initially evaluate total energy use and greenhouse gas (GHG) emissions from pavement maintenance and rehabilitation (M&R) strategies. This LCA model allows analysis of the energy consumption and GHG emissions associated with material production, construction, and vehicle operation during pavement use, which includes the effects of pavement roughness and texture on vehicle operation. The model was used to evaluate four case studies of Caltrans (California Department of Transportation) pavement preservation treatments for both asphalt and concrete surfaces with different roughness and texture and traffic levels. For highways with high traffic volumes, results of the case studies show that the energy and GHG savings accrued during the Use Phase (due to reduced roughness and macrotexture change) can be significantly larger than the energy use and GHG emissions from material production and construction. The extent of the benefit was dependent on constructed smoothness with a much smaller benefit from change of texture. These savings can be larger than those from other strategies meant to reduce highway transportation energy use and emissions. For low traffic volume highways, the smoothness obtained by the contractor and the materials used determine whether the net effect on GHG emissions and energy use is positive or negative.

Estimating the Effects of Pavement Condition on Vehicle Operating Costs, NCHRP Report 720, 2012.
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_720.pdf
Chapter 3 includes a fuel consumption model with variables including pavement roughness. Findings include (page 55):

> For fuel consumption, the most important factor is surface roughness (measured using IRI). An increase in IRI of 1 m/km (63.4 in./rni) will increase the fuel consumption of passenger cars by about 2% irrespective of speed. For heavy trucks, this increase is about 1% at normal highway speed (96 kmh or 60 mph) and about 2% at low speed (56 km/h or 35 mph). Surface texture (measured by MPD) and pavement type do not affect the fuel consumption of any vehicle class except for heavy trucks. An increase in MPD of l mm will increase fuel consumption by about 1.5% at 88 kmh (55 mph) and about 2% at 56 km/h (35 mph).

See page 56 for Table 7-1, summarizing the effects of roughness on fuel consumption:

Table 7-1. Effect of roughness on fuel consumption.

Speed	Vehicle Class	Base (mL/km)	Adjustment Factors from the Base Value					Base (mpg)	Adjustment Factors from the Base Value				
		IRI (m/km)						IRI (m/km)					
		1	2	3	4	5	6	1	2	3	4	5	6
56 km/h (35 mph)	Medium car	70.14	1.03	1.05	1.08	1.10	1.13	33.53	0.97	0.95	0.93	0.91	0.88
	Van	76.99	1.01	1.02	1.03	1.04	1.05	30.55	0.99	0.98	0.97	0.96	0.95
	SUV	78.69	1.02	1.05	1.07	1.09	1.12	29.89	0.98	0.95	0.93	0.92	0.89
	Light truck	124.21	1.01	1.02	1.04	1.05	1.06	18.94	0.99	0.98	0.96	0.95	0.94
	Articulated truck	273.41	1.02	1.04	1.07	1.09	1.11	8.60	0.98	0.96	0.93	0.92	0.90
88 km/h (55 mph)	Medium car	83.38	1.03	1.05	1.08	1.10	1.13	28.21	0.97	0.95	0.93	0.91	0.88
	Van	96.98	1.01	1.02	1.03	1.04	1.05	24.25	0.99	0.98	0.97	0.96	0.95
	SUV	101.29	1.02	1.04	1.07	1.09	1.11	23.22	0.98	0.96	0.93	0.92	0.90
	Light truck	180.18	1.01	1.02	1.03	1.04	1.05	13.05	0.99	0.98	0.97	0.96	0.95
	Articulated truck	447.31	1.02	1.03	1.05	1.06	1.08	5.26	0.98	0.97	0.95	0.94	0.93
112 km/h (70 mph)	Medium car	107.85	1.02	1.05	1.07	1.09	1.12	21.81	0.98	0.95	0.93	0.92	0.89
	Van	128.96	1.01	1.02	1.03	1.03	1.04	18.24	0.99	0.98	0.97	0.97	0.96
	SUV	140.49	1.02	1.04	1.06	1.08	1.10	16.74	0.98	0.96	0.94	0.93	0.91
	Light truck	251.41	1.01	1.02	1.02	1.03	1.04	9.36	0.99	0.98	0.98	0.97	0.96
	Articulated truck	656.11	1.01	1.02	1.04	1.05	1.06	3.58	0.99	0.98	0.96	0.95	0.94

"Evaluation of the Impact of Pavement Roughness on Vehicle Gas Emissions in Baltimore County," *Transportation Research Board 91st Annual Meeting,* Paper 12-2872, 2012.
http://docs.trb.org/prp/12-2872.pdf
This study investigated the correlation between vehicle gas emissions and pavement roughness in Maryland, using IRI and roadway speed data and calculating emissions using MOVES2010a, a vehicle emission modeling software program. Researchers concluded that gas emission quantities will increase as the vehicle speed is decreasing or in other words as the pavement roughness is worsening. Table 5 includes estimated emissions reductions depending on pavement roughness (page 13):

TABLE 5 MOVES2010 Results Per Passenger Car

POSTED SPEED (MPH)	AVERAGE SPEED (MPH)		CO_2 Equivalent EMISSIONS (GRAMS)		CHANGE IN CO_2 Equivalent EMISSIONS (GRAMS)
	Poor	Good	Poor	Good	$\Delta_{\text{Poor to Good}}$
30	42.34	-	245	-	-
35	41.22	-	-	-	-
40	44.08	47.04	243	239	-4
45	-	48.53	-	-	-
50	48.28	54.10	238	233	-5
55	55.67	66.84	231	241	+10
65	-	68.10	-	-	-

"Coeee: CO_2 Emission Reduction by Exploitation of Rolling Resistance Modelling of Pavements," *Eurasphalt & Eurobitume Congress,* 2012.
Abstract at http://trid.trb.org/view/2012/C/1216727
From the Abstract: As it is estimated that 25 percent of the CO_2 emitted on the roads is caused by rolling resistance it is expected that 3-5 percent on fuel consumption can be saved by developing and implementing new low rolling resistance pavement types. A savings of 3 to 5 percent fuel is equivalent to at least 48 million liters of fuel saved annually in Denmark. That savings will provide 45,000 tons less greenhouse gases as CO_2 and 76 tons less nitrogen oxides (NOx) in Denmark alone. Seen in a socio-economic perspective it will ideally be possible to save 40 million EUR in Denmark when the expected output is implemented. The project covers subjects such as novel pavements, wear and aging, models of rolling resistance, measuring rolling resistance and asset management systems.

"Life Cycle Energy Consumption and GHG Emission from Pavement Rehabilitation with Different Rolling Resistance," *Journal of Cleaner Production*, Volume 33, September 2012, pages 86-96.
http://www.sciencedirect.com/science/article/pii/S0959652612002235
Abstract: This paper describes a pavement life cycle assessment (LCA) model developed to evaluate energy use and greenhouse gas (GHG) emissions from pavement rehabilitation strategies. The LCA model analyzes the energy and GHG emissions associated with material production, construction and pavement use, which includes the effects of pavement rolling resistance on vehicle operation. The model was used to evaluate a set of case studies of pavement rehabilitation for both asphalt and concrete surfaces with different rolling resistances and traffic levels. The primary goal of the case studies is to evaluate the effect of rolling resistance on the life cycle performance of pavements, not to compare asphalt and concrete pavements. Energy and GHG emission savings from pavement rehabilitation are compared with an alternative where no rehabilitation occurs, only routine maintenance of damaged pavement. The results of the case studies show that for highway sections with high traffic volumes the energy and GHG savings accrued during the use phase due to reduced rolling resistance can be significantly larger than the energy use and GHG emissions from material production and construction, with the extent of the benefit dependent on constructed smoothness. These savings can be larger than those from other strategies to reduce highway transportation energy use and emissions, such as projected improvements in vehicle fuel economy. For low traffic volume highways, the smoothness obtained by the contractor and materials used have a more significant effect on the performance of the rehabilitation, and may result in a net increase in

energy use and GHG emissions if low traffic volumes and poor construction quality occur together.

"A Field Investigation of the Effect of Pavement Type on Fuel Consumption," *First Congress of Transportation and Development Institute,* 2011.
Abstract at http://trid.trb.org/view/2011/C/1109530
Abstract: Fuel consumption costs are influenced by vehicle technology, pavement condition, roadway geometrics, environment, speed, and other factors. The goal of this paper is to investigate the effect of pavement type on fuel consumption. The study has entailed the use of five instrumented vehicles to make fuel consumption measurements over different concrete (PCC) and asphalt (AC) pavement sections. The sections selected have similar characteristics (grade, roughness and texture) and differ only in the type of pavement. The data was collected at three different speeds. The results showed that the difference in fuel consumption between asphalt and concrete pavements is statistically significant at 95 percent confidence level for (loaded) light and heavy trucks at low speed (56 km/h) and summer conditions. Under these conditions, trucks driven over AC pavements will consume about 4 percent more than if they were driven over PCC pavements. Fuel consumption data for heavy truck in winter was not available. The analysis also showed that the mean differences of fuel consumption between asphalt and concrete pavements for passenger car, van and SUV are statistically not significant for both winter and summer conditions.

"A General Overview of Research Efforts at the NCAT Pavement Test Track," E. R. Brown and R. B. Powell, *Proceedings of the Second International Symposium on Maintenance and Rehabilitation of Pavements and Technological Control*, 2001.
Abstract at http://trid.trb.org/view.aspx?id=700353
This study concludes that a change of 6 in IRI from 1.08 m/km (68 in/mi) to 1.18 m/km (75 in/mi) results in a 2 percent fuel consumption increase.

"Roads, Vehicle Performance and Greenhouse: Costs and Emission Benefits of Smoother Highways," Australia Bureau of Transport and Communications Economics working paper, Issue 32, 1997.
Abstract at http://trid.trb.org/view/1997/C/476050
This paper evaluates the effects on greenhouse gas emissions and vehicle operating costs of reducing the roughness of the Australian National Highway System and the Pacific Highway from 1996 to 2015. It includes a review of the relationships between pavement surface condition and speed, skid resistance and rolling resistance/fuel consumption, and between speed and fuel consumption. The results of the analysis indicate that reducing the roughness of highways has the potential to produce modest reductions in cumulative emissions over time.

"Road Macro- and Megatexture Influence on Fuel Consumption," *Surface Characteristics of Roadways: International Research and Technologies*, 1990: 460-479.
This study found that a change in pavement roughness from smooth to rough could increase fuel consumption by as much as 12 percent. However, a numerical relationship could not be determined due to external factors that made it difficult to isolate the effect that pavement roughness alone had on fuel consumption.

Contacts

CTC contacted the individuals below to gather information for this investigation.

State Agencies

Oregon
Amanda Pietz
Planning Unit Manager
Oregon Department of Transportation
503-986-4227, amanda.pietz@odot.state.or.us

Tara Weidner
Integrated Transportation Analysis Engineer
Oregon Department of Transportation
503-986-4226, Tara.J.Weidner@odot.state.or.us

Washington
Seth Stark
Sustainable Transportation Manager
Washington State Department of Transportation
360-628-7611, StarkS@wsdot.wa.gov