The 48th Annual A&WMA Critical Review

Trends in Onroad Transportation Energy and Emissions

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Summary Article in June 2018 EM

Trends in Onroad Transportation Energy and Emissions
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Introduction
Over the last 100 years, the automobile has been responsible for major social and economic trends in land use and personal mobility. U.S. registered on-road vehicles grew from 8.00 million in 1900 to 268 million in 2015 (Bureau of Transportation Statistics, 2016; Federal Highway Administration, 1997). From 1950 to 2018, U.S. road miles increased by 28% whereas vehicle miles traveled (VMT) increased by 69% (Figure 1). Increases in vehicle fuel economy have helped to offset growth in vehicle miles traveled. As a response to the 1973 oil embargo (U.S. Department of State, 1980), the 1975 Energy Policy and Conservation Act established Corporate Average Fuel Economy (CAFE) standards that were effective with the 1976 model year (U.S. Congress, 1975). In 2009, the U.S. Environmental Protection Agency (EPA) issued an endangerment finding for six greenhouse gases (GHGs) because of their contribution to climate change (EPA, 2009). The U.S. Department of Transportation (USDOT) and EPA issued new fuel economy and tailpipe exhaust emission standards for carbon dioxide (CO2), effective for the 2012 model year for light-duty vehicles (LDVs) and effective with the 2014 model...
Summary Article in June 2018 EM

Plus... Supplemental Materials

50-page Paper in June 2018 Journal of A&WMA
Scope of the Critical Review

• National and Global Energy Use and Emissions
• Factors Affecting Travel Demand and Vehicle Operation
• Vehicle Energy Consumption
• Vehicle Emissions
• Measurement Methods
• Impacts on Exposure and Health
Underlying Factors
Number of Registered Onroad Vehicles in the U.S.

![Graph showing the number of registered onroad vehicles in the U.S. from 1900 to 2020. The graph includes data from FHWA and BTS/USDOT, with a trend line indicating an increase over time.](image_url)
1970

• U.S. on-road vehicle contributions to national emissions
  • 35% of Nitrogen Oxides (NO\textsubscript{x})
  • 68% of Carbon Monoxide (CO)
  • 42% of Volatile Organic Compound (VOC)

• U.S. Environmental Protection Agency was formed

• Clean Air Act mandated vehicle emission standards

• California allowed to request a waiver under the Clean Air Act
Health Burden

- Air pollution from motorized road transport
- Premature death
- Global estimates range between 184,000 and 242,000 (Bhalla et al., 2014; Chambliss et al., 2014)
- Based on fine particulate matter (PM$_{2.5}$)

- By country:
  - India (39,000)
  - China (27,000)
  - U.S. (15,000)
Global In-Use Onroad Vehicle Stock

44% Increase Over 10 Years

Source: OICA, 2018
Factors Affecting Travel Demand and Vehicle Operation

- Street connectivity
- Land-use patterns
- Dwelling density
- Distance to transit
- Sidewalks
- Income level
- Vehicle purchase tax
- Vehicle ownership tax
- CO$_2$ emission tax
- Cordon pricing
- Parking fees
- Low emission zones
Global Annual Onroad Vehicle Sales

42% Increase

Source: OICA, 2018
Energy

On-road transportation accounts for 13% of global energy use
79.4 Quadrillion BTU
Annual Global Consumption of Diesel Fuel, 1986-2014

80% Increase

Source: EIA, 2018
Annual Global Consumption of Gasoline Fuel, 1986-2014

North America
Europe
Asia & Oceania
All Other

33% Increase

Source: EIA, 2018
Global Onroad Vehicle Energy Consumption: Actual to 2014, Projected Thereafter

Source: EIA, 2017d

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Global Onroad Vehicle Energy Consumption: Actual to 2014, Projected Thereafter

33% Projected Increase From 2014 to 2050

Source: EIA, 2017d
Projected U.S. Onroad Vehicle Energy Consumption by Fuel Source

Assumes Current Fuel Economy and GHG Emission Standards

Source: EIA, 2017a
Errors in Energy Projections

• Predictions often fall outside range of estimated error bounds
• Trends in underlying assumptions often not consistent with later reality
• Prediction intervals based on past errors in projections can exceed ±5 Quads in 10 years
• Nonetheless, projections can be helpful as a planning tool
• ‘All projections are wrong, some are useful’
Autonomous Vehicles

• Uncertainties regarding market share in 2030, 2050
• Legal issues, social acceptance, institutional adaptation
• Could reduce travel delay and improve travel time reliability
• Could be inherently safer
• Could have shared AVs that are “right-sized”
• Platooning, efficient routing, efficient driving
• Possibly lower “cost” of travel, more accessibility
• Long-term effect on land-use patterns
• Adaptive traffic management via dynamic road pricing or other schemes
• Could decrease or increase energy consumption and emissions
U.S. Light Duty Vehicle Fuel Economy Trends

Source: EPA, 2018

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Trends in U.S. Light Duty Vehicle Technology: Fuel Delivery

Source: US EPA, 2018
Gas Direct Injection

“Wall-Guided” Example

http://www.climatetechwiki.org/technology/ice_improvements
Trends in U.S. Light Duty Vehicle Weight and Horsepower

Source: US EPA, 2018

Increasing share of downsized turbo-charged engines
U.S. Sales (1,000s) of Electrified Powertrain Vehicles from 2011 to 2017

https://autoalliance.org/energy-environment/advanced-technology-vehicle-sales-dashboard/
Greenhouse Gas Emissions

• Global road transport emissions grew from \(3.3 \text{ GtCO}_2\) in 1990 to \(5.7 \text{ GtCO}_2\) in 2015 (18% of global emissions)

• For road transport in the U.S., \(\text{CO}_2\) contributes 96.4% of the total global warming potential, followed by HFCs (2.8%), \(\text{CH}_4\) (0.7%), and \(\text{N}_2\text{O}\) (0.1%).

• In the U.S., GHG emissions are up 16% for passenger cars and 79% for trucks since 1990.
Greenhouse Gas Emissions

• From 2010 to 2050, GHG emissions from light duty vehicles could be reduced by 39% to 76% depending on global region and adoption of new technologies.

• Potential reductions for freight transport are smaller, at 31% to 33%

• GHG emissions reductions, examples:
  • CNG – depends on pipeline fugitive emissions
  • Hydrogen – depends on source (steam reforming of CH₄)

• Actual trend: increases are likely to continue
EPA Light Duty Vehicle GHG Emissions Standards

- Mid-Term Evaluation, January 2017: standards are appropriate
- Reconsideration, April 2, 2018: standards are “not appropriate”
- EPA Science Advisory Board:
  - “The April 2, 2018 final determination relied extensively on public comment without peer review or independent evaluation or validation of claims made by public commenters.”
  - “The SAB should consider this action for review with regard to the adequacy of the supporting science”
Battery Electric: Zero Emissions or Coal-Fired Vehicle?

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Sensitivity of Battery Electric Vehicle CO₂ Emissions to U.S. State Energy Mix

Data Source: US DOE/AFDC (2018)
Electric Vehicles: A Panacea?

• The U.S. Clean Power Plan was an attempt at the Federal level to reduce GHG emissions from power generation
• Regulatory actions are in progress to rescind, revise, or replace the Clean Power Plan
• State renewable energy portfolio standards can be effective
Emissions
Methods for Managing Emissions

Emission reductions → Cleaner air & better health

- **Catalytic converters** in conjunction with unleaded gasoline and low sulfur levels significantly reduce hydrocarbon & nitrogen oxide emissions
- **Fuel standards** reduce exposure to pollutants like lead and benzene
  - Renewable fuels reduce CO₂ emissions
- **Engine technologies** like computer controls, variable valve timing, multi-valve engines, turbo charging & gasoline direct injection improve fuel economy & reduce CO₂ emissions
- **Transmission technologies** like 7+ speeds, dual clutch transmissions (DCTs), & continuously variable transmissions (CVTs) improve fuel economy & reduce CO₂ emissions
- **Diesel filters** reduce particulate matter from on road & off road diesel engines
- **Alternative vehicle technologies** like plug-in electric vehicles & fuel cells = zero tailpipe emissions
- **Better transportation planning** for passengers & freight reduce emissions & fuel use

https://www.epa.gov/air-pollution-transportation/learn-about-air-pollution-transportation

Source: EPA, 2018
Fuels

• Clean Air Act Amendments of 1990
  • Reduced gasoline sulfur content
  • Lower gasoline volatility
  • Use of oxygenated reformulated fuels
• 2005 Energy Policy Act led to blending of ethanol as oxygenate
• Most gasoline sold in the U.S. is E10
Sulfur

• Post-combustion controls are adversely affected
  • Three Way Catalyst (TWC)
  • Selective Catalytic Reduction (SCR)
  • Diesel Oxidation Catalyst (DOC)
  • Diesel Particle Filter (DPF)

• Low sulfur fuels are essential to high efficiency post-combustion control of NO$_x$, CO, and HC from gasoline engines and NO$_x$ and PM from diesel engines
Three Way Catalyst

• Fully implemented in 1996
• Estimated to have reduced emissions through 2007:
  • 4 billion tons of HC
  • 4 billion tons of NO$_x$
  • 40 billion tons of CO
  Source: Mooney, 2007
• Widely applicable to stoichiometric burn engines
Emissions Processes: \( \text{NO}_x \) Emissions

Gasoline Passenger Cars

Based on MOVES2014a

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Emissions Processes: Total Hydrocarbon Emissions

Based on MOVES2014a

Gasoline Passenger Cars
- Running Exhaust
- Start Exhaust
- Crankcase Running
- Crankcase Start
- Leaks
- Venting
- Permeation
- Displacement
- Spillage

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Vehicle Emission Controls: Diesel Particle Filter (PDF)

Widely used in U.S. on-road diesel trucks since 2007

Removes more than 95% of particle mass and 99% of particle number

Particles emitted from DPF-equipped vehicles tend to be very small (nucleation mode)
Vehicle Emission Controls: Selective Catalytic Reduction

- Widely used in U.S. on-road diesel trucks since 2010
- Requires urea: “diesel exhaust fluid”
- Requires sufficient operating temperature
- May not be effective at low exhaust temperature
Trends in NO\textsubscript{x} Emission Factors: 1990 to 2050

Based on MOVES2014a
Trends in NO\textsubscript{x} Emissions Source Distribution: 1990 to 2050

Based on MOVES2014a
Ask Me About Gliders… new chassis with an old model year engine

Complete cab assembly with OEM windshield instrument panel and interior appointments customized to your specifications

AC compressor & power steering pump, brackets and mounting hardware are included in the loose parts box

Factory installed air cleaner & filter

New hood, fenders, grille and bumper with your choice of finish

Radiator, shroud & charge air cooler are pre-installed at the factory

Engine prep for most popular diesel engines

New steer axle with wheel ends, brakes, wheels & tires built to your specs

Prep packages for a variety of transmissions are available for factory installation

OEM battery cables are included in the loose parts box

OEM exhaust piping components and mounting hardware are included in the loose parts box EPA 96-04 engines only

Factory chassis built just like new tractors

Optional factory-installed rear axle, wheels and tires

Stop, turn and back-up lights with brackets and fasteners

Rear mud flaps, mounting brackets and hardware

THE MOST COMPLETE KIT
AVAILABLE ANYWHERE
Quality of Emissions Estimates

• Uncertainties are rarely quantified
• NARSTO (2005) characterized confidence levels in on-road mobile source emission inventories:
  • Medium-high for NO\textsubscript{x}
  • Low-medium for VOC
  • Low-medium for hazardous air pollutants
• National Research Council report on mobile source modeling (2000)
• Subsequently, EPA replaced Mobile6 with MOVES
MOVES Reforms Since NRC (2000)

• Emission factors from frequency distributions  
• Evaluations of model predictions using independent data  
• Advisory group of external experts  
• Sensitivity analysis  
• Could do more on uncertainty analysis
Validity of Estimated Trends in Emissions

• Numerous studies have measured vehicle emission rates over time based on remote sensing, tunnel studies, chassis dynamometer, plume-chasing, road side air quality, and other measurements.

• In the U.S., consistent evidence of decreasing CO, NO$_x$, HC, and Mobile Source Air Toxic (MSAT) emission rates.

• Example: Los Angeles basin mobile source NO$_x$ emissions peaked in 1986 and have since decreased by 65% through 2015.

• Some concerns regarding accuracy of NO$_x$ emissions estimates:
  • Operability, durability and long-term effectiveness of diesel NO$_x$ control?
  • Manufacturer “cheating”?
  • Mismatch of model input assumptions with site-specific reality?
  • Gliders?
Empirical Trends in Vehicle Emissions (Example)

• From 1990 to 2010, onroad CO emission rates decreased by 80% to 90% in Los Angeles, Houston, and New York
• From 1990 to 2012, ambient concentrations of diesel particulate matter decreased by 68% in California
• VOC emissions have decreased
Secondary Organic Aerosols

• SOA Precursors
  • Intermediate Volatile Organic Compounds (IVOCs): 13-19 carbon atoms
  • Semi-Volatile Organic Compounds (SVOCs): 20-26 carbon atoms

• Sub-micrometer particles

• SOA formation depends on atmospheric chemistry (e.g., peroxy radicals)

• SOA yield appears to have decreased from 1970 to 2010 by approximately 33% to 50%

May et al., 2014
Emissions Scandals

• 1999: heavy duty diesel engine manufacturers used a “defeat device” that increased real-world NO\textsubscript{x} emissions.

• 2005: New test procedures finalized
  • “not to exceed” emission limits
  • Can be measured on engine dynamometer or using Portable Emission Measurement Systems (PEMS)

• 2014: VW excess emissions uncovered by VWU using PEMS
“Real Driving Emissions” (RDE)

• 90 percent of measured vehicles had real-world NO\textsubscript{x} emission rates higher than the Euro 6 limit (Baldano et al., 2017)

• EU regulatory approach
  • lower power demand cycles than used in the U.S.
  • lacks in-use surveillance

• The European Union has implemented requirements to measure Real Driving Emissions (RDE) using PEMS.
Inspection and Maintenance (I/M)

• 1992: EPA issued regulation requiring all I/M programs to use dynamometer-based tests

• 2001: EPA abandoned this requirement in favor of On-Board Diagnostic (OBD) system checks

• “Lack of overlap” between emission tests and OBD system checks. e.g., in Colorado:
  - 3,000 vehicles failed OBD
  - 400 vehicles failed emissions tests
  - Only 66 vehicles failed both tests

• Deterioration of the OBD system not well understood
Measurement Methods

- Chassis dynamometer
- Engine dynamometer
- Tunnel studies
- Remote sensing
- Chase vehicles
- Portable emission measurement systems
- Mobile emissions laboratories
- Automotive sensors
- Twin site ambient measurements
- Inverse modeling
- Evaporative emissions
- Low cost sensors

Discussed in more detail in the Critical Review paper and its Supplemental Material
Transportation, Exposure, and Health

- Evidence for and estimates of the health effects of traffic-related air pollution
- Empirical evidence regarding near-road exposure concentrations
- Empirical evidence regarding in-vehicle exposures
- Methods for modeling human exposure

Discussed in more detail in the Critical Review Supplemental Material
Other Points...
Emissions

• Areas for ongoing assessment:
  • Durability and operational limitations of diesel post-combustion controls
  • Life cycle inventories of alternative fuels/energy sources
  • Mobile Source Air Toxics (MSATs)
  • Speciated PM
  • Ultrafine PM
  • Secondary Organic Aerosols
Wear Emissions

• Tire wear is relevant to any vehicle with tires
• Brake and tire wear emissions relatively weakly quantified
Greenhouse Gas Emissions

• Growth in vehicle stock, VMT, and fossil fuel consumption will lead to increase in GHG emissions

• Unless… priorities to reduce carbon intensity of transportation energy consumption are pursued – e.g.,
  • Increasingly stringent fuel economy standards
  • Increased vehicle electrification coupled with lower carbon power generation
Measurement Methods

• Emerging sensor and measurement technologies may enable more stakeholders to conduct their own measurements
Exposure and Health

More work is needed to characterize spatial and temporal variability in emissions, exposure, and adverse effects related to transportation.
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Supplemental Materials
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