The National Academies of

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BOARD ON ENERGY AND ENVIRONMENTAL SYSTEMS

# Reducing the Fuel Consumption and Greenhouse Gas Emissions of Medium- and Heavy-Duty Vehicles, Phase Two

Final Report

Committee on Assessment of Technologies and Approaches for Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles, Phase Two

Chair – Dr. Andrew Brown Jr., NAE
Study Director: Dr. Beth Zeitler

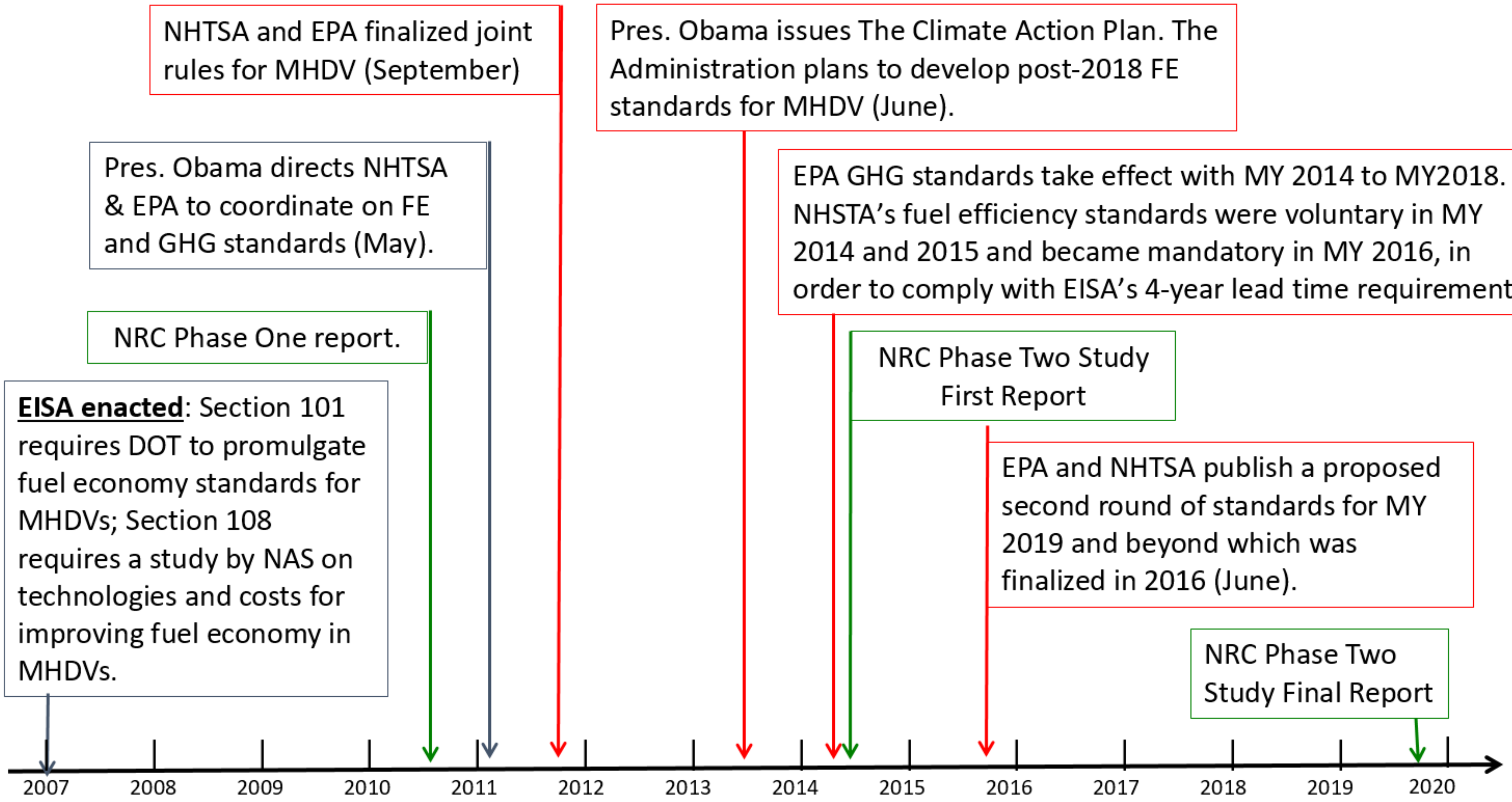
Overview Presentation of Report
National Academies
Washington, DC

Report available at nap.edu/25542

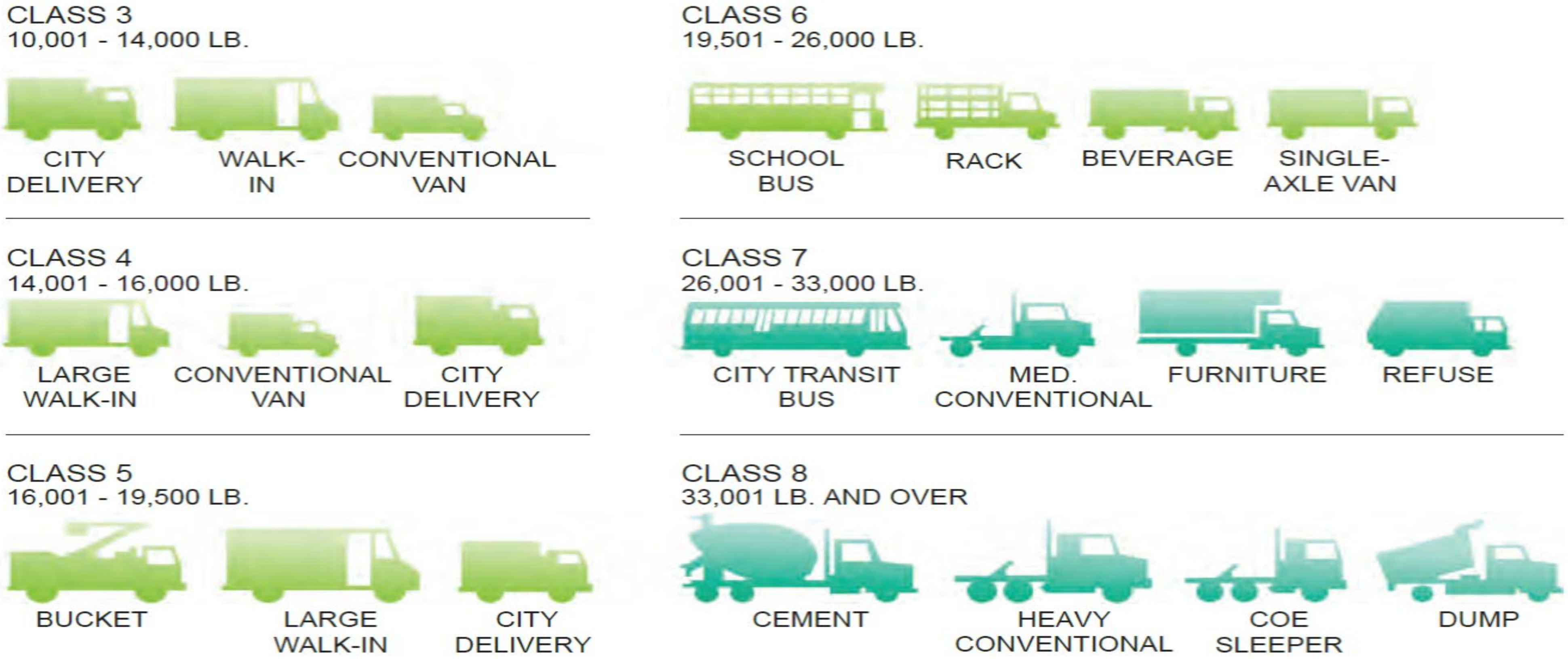
# OUTLINE

- ❑ **Introduction & Background**
  - ❑ Charter & Mandates
  - ❑ MHDV Regulation Timeline
  - ❑ Regulatory Phases
  - ❑ MHDVII Committee Members
- ❑ **Organization & Execution**
- ❑ **Concluding Recommendation – Interim Evaluation**
- ❑ **Summary of Key Take-Aways**
- ❑ **Vehicle Technology Progress**
- ❑ **Alternative Technology & Approaches**
  - ❑ Hybridization
  - ❑ Fuel Considerations
  - ❑ Improved Freight Movement Efficiency
- ❑ **Economic Assessment & Considerations**
- ❑ **Future Regulatory Framework**
- ❑ **Question & Answer Session**

# FIGURE 1-1 KEY EVENTS IN MHDV REGULATION TIMELINE



# FIGS. 2-10 & 2-11 SIZE & WEIGHT CLASSES OF MHD VEHICLES




CLASS 2B
8501-10,000 LB.

# STATEMENT OF TASK(1)

1. **Review and contrast the final rule** for fuel efficiency and greenhouse gas emissions standards for medium- and heavy-duty engines and vehicles for model years 2014-2018 with the recommendations offered in the NRC 2010 report.
2. Analyze and provide options for **improvements to the certification and compliance procedures** for medium- and heavy-duty vehicles, including the use of representative test cycles and simulation using EPA's GEM.
3. **Review updated baseline information** on the medium- and heavy-duty truck fleet, including combination tractors and trailers, as well as the methodology for providing on-road information on fuel consumption necessary to inform baseline standards.
4. **Examine advanced gasoline engine technologies**, including the ability of those engines to meet load demands, the impact of those engines on cost, the need for after-treatment systems, and their market acceptability.
5. **Examine diesel emission control systems**, including the capabilities of emission control systems to meet current and possible future criteria pollutant emissions standards, the impacts on fuel consumption attributed to meeting emissions standards, and the fuel characteristics needed to enable low-emissions diesel technologies.
6. **Examine electric powertrain technologies**, including the capabilities, limitations, and cost of hybrids, plug-in hybrids, battery electric vehicles, and fuel cell vehicles
7. **Examine battery technologies** including an examination of the cost, performance, range, durability (including performance degradation over time), and safety issues related to lithium-ion and other possible advanced energy storage technologies that are necessary to enable plug-in and full-function electric vehicles.

# STATEMENT OF TASK (2)

8. **Examine vehicle technologies** such as mass reduction, aerodynamic drag improvements, automatic tire inflation systems, improved transmissions, improved efficiency of accessories, fans, and water pumps, and other approaches.
9. **Evaluate intermodal and intelligent systems** for potential fuel consumption benefits, including a survey of the current fleet communication systems (vehicle to vehicle, vehicle to infrastructure), existing barriers to implementation, and future technologies.
10. **Review the potential impacts of fuel-consumption-reduction technologies on medium- and heavy-duty vehicle safety** including aerodynamic components, wide-based wheels and tires, tire pressure monitoring and automatic inflation systems, hybridization and alternative fuels, combination vehicles and higher gross vehicle weight ratings, lightweighting, idle reduction and stop-start, and others.
11. Provide an analysis of how fuel efficient technologies may be practically **integrated into manufacturing processes** and how such technologies are likely to be applied in response to requirements for reducing fuel consumption.
12. **Examine the costs, cost multipliers, and benefits** that could accompany the introduction of technologies for reducing fuel consumption.
13. To the extent possible, **address uncertainties and perform sensitivity analyses** for the fuel consumption and cost-benefit estimates and provide guidance to NHTSA on improving its uncertainty analyses given the relatively long time frame for these future estimates.
14. **Write and provide to NHTSA, the Congress, and the public a final report** documenting its conclusions and recommendations.

# The 17 member committee contributed diverse expertise in MHDV technology, engineering, production, commercialization, regulation and economics.

**Dr. Andrew Brown, Jr** (NAE), Delphi Automotive, *Retired*, *Committee Chair*

**Dr. Inês Azevedo,** Stanford University

**Dr. Rodica Baranescu** (NAE), University of Illinois, Chicago, *Retired*

**Mr. Thomas Cackette**, California Air Resources Board, *Retired*

**Dr. Nigel Clark**, West Virginia University

**Dr. Ron Graves**, Oak Ridge National Laboratory, *Retired*

**Mr. Daniel Hancock** (NAE), General Motors, *Retired*

**Dr. Michael Hanemann** (NAS), Arizona State University

**Dr. Winston Harrington**, Resources for the Future

**Dr. Gary Marchant**, Arizona State University

**Mr. Paul Menig**, Tech-I-M, LLC

**Mr. Michael Roeth**, North American Council for Freight Efficiency

**Mr. Gary Rogers**, Roush Industries, LLC

**Mr. Charles Salter**, Consultant

**Ms. Christine Vujovich**, Cummins, Inc., *Retired*

**Mr. John Woodrooffe**, University of Michigan

**Dr. Martin Zimmerman**, University of Michigan

# ORGANIZATION & EXECUTION

- **Expertise-based Task Teams** MHDVII Committee organized into 5 task teams based on expertise and responding to the individual tasks. It tasked the Southwest Research Institute to conduct combustion simulation and competitive technology studies for the report.
- **Industry Interviews** Conducted several industry, agency, research & user site visits.
- **Public Presentations** Received numerous presentations from companies, government agencies and various non-profit/research organizations.
- **Final Report** Completed a comprehensive final report with 67 major recommendations.
- **Report Delay** This final report was delayed due to the absence of funding and resources. It contains a summary, 13 chapters and approximately 106 significant findings.

# Concluding Recommendations

**An interim evaluation** of its MHDV regulation in the 2021-2022 time period would help improve the regulation's overall effectiveness and value. The evaluation's primary focus would be on preparations for any future regulations beyond the Phase 2 standards. The interim evaluation (IE) would address the following tasks:

## Vehicle Technologies

1. **Drag:** Re-test MHDVs in marketplace to establish progress in reducing aerodynamic drag. Evaluate progress in CFD and computational power to consider greater application of simulation in this field. The impacts of the ambient turbulence intensity and close-proximity vehicle passing turbulence scenario should be evaluated to quantify its significance on real-world aero drag.
2. **LDV Synergy:** Assess the extent that high-efficiency technologies emerging in light-duty SI engines will map to MHDVs.
3. **Diesel Engines:** Review progress in diesel engine efficiency and emissions, noting the possibility of new engine platforms.
4. **Class 2b:** Assess progress in engines for Class 2b heavy pickups and vans, as well as progress at the vehicle level, and assess whether benefits of available technologies are being captured.
5. **Criteria Pollutants:** Assess the fuel consumption benefits of improved diesel engines under more stringent NOx standards, considering the overall cost effectiveness and impact on efficiency and market share of diesels.
6. **Vocational:** Assess the status of engines for vocational vehicles and whether the benefits of available technology improvements are being captured in the marketplace as driven by Phase 2 regulations.

# Alternative Technologies & Approaches

1. **SI Engines and Gasoline:** Consider and further analyze scenarios where SI engines and gasoline-like fuels play a larger role in freight movement, especially giving consideration and analysis to the impact of higher octane fuels with or without renewable fuel content. Consider the balance between gasoline and diesel (distillate) fuel production at the refineries.
2. **Natural Gas Trucks:** Evaluate progress in reducing the efficiency gap between natural gas engines and diesel/gasoline fueled engines and re-assess the overall GHG benefits of natural gas trucks. Determine updated energy balances for MHDVs with new technologies and representative duty cycles.
3. **Materials Joining and Manufacturing:** Assess the progress of additive manufacturing, materials joining processes, nanostructured materials, and other yet-to-be-identified promising manufacturing innovations—as well as their prioritization status, and prognosis for effective commercialization for the Phase 3 regulatory period.
4. **GHG and FC Reduction from Fuel Mix**: Assess the future balance in MHDVs between SI and diesel, and the reductions in GHG and fuel consumption that might be achieved with more efficient SI engines, including an optimized low-carbon or renewable fuel.
5. **Low Temperature Combustion:** The status of LTC should be followed and reassessed in comparison to advanced conventional combustion engines, including the applicability of WHR to both engine systems.
6. **Alternative Configurations:** Assess the potential of alternative configuration engines to surpass the improvements in fuel consumption envisaged for advanced conventional combustion engines.
7. **Automation:** Assess progress in automation for MHDVs

## Improved Freight Movement Efficiency

1. **Intermodal:** Assess improvements in intermodal transfer facilities
2. **Operations:** Assess operational improvements such as improvements in freight transfer facilities near major highways.

## Economic Assessment & Considerations

1. **In-Use Measurement:** If and when widespread adoption of in-use measurement of fuel use or emissions comes about, serious consideration should be given to the adoption of a cap and trade system or fuel taxes that directly target fuel consumption or emissions for future phases of MHDV rule making.

## Future Regulatory Framework

1. **Evaluate Impact of Previous Regulations:** Evaluate fleet performance under previous phases of regulation. This evaluation would include actual technology costs, efficiencies realized, and technology penetration rates compared to assumptions in previous RIAs.
2. **Cost-Effectiveness:** Estimate the cost-effectiveness of rules adopted and prospective rules in light of technology developments and fuel prices.
3. **In-use Compliance:** Assess progress in in-use monitoring technology and feasibility analysis of in-use compliance monitoring.

## SUMMARY OF KEY TAKE-AWAYS

- New fuel and power source options (including WHR, hybrid-electric systems and auxiliary power sources) may be needed to achieve significant further progress in reducing fuel consumption and GHG emissions from MHDVs over the next couple of decades
- Implementation of new propulsion technologies, new low-carbon fuels, and more efficient freight operations and logistics may offer the opportunity to reduce GHG emissions beyond what is achievable from improving the efficiency of combustion engine MHDVs.
- With respect to hybridization of commercial vehicles, several international light-duty vehicle manufacturers and Tier 1 battery suppliers are projecting costs for plug-in hybrid-electric or battery electric vehicle battery packs that will achieve \$120/kWh by 2020 and \$100/kWh or less by 2025. In 2027 and beyond, stop-start technology applications are expected to have payback periods that would make them attractive in many applications to private firms.
- **A range of opportunities exists to improve energy efficiency and reduce GHG emissions in freight transportation**. For example, modifying truck size and weight standards, facilitating intermodal shipments, and truck platooning could improve the fuel efficiency of freight shipments. Also, the committee found that **higher weight limits and longer combination vehicles could significantly improve productivity**

## SUMMARY & KEY TAKE-AWAYS

- The Agencies should employ a simpler and more transparent method and rationale on how the unit costs of technologies will evolve, either over time or as a function of the production capacity, in their future assessment.
- NHTSA and the EPA currently lack reliable data on real-world vehicles that can be used to establish a credible regulatory baseline. It is essential for evaluating the effectiveness and success of the regulatory program and identifying future regulatory priorities and directions.
- An effective method of determining in-use fuel consumption of trucks, and thereby of determining the overall effectiveness of the regulatory program, is not currently feasible technologically. Given that NHTSA's Phase II rule covers model years through 2027, the agencies have sufficient time to explore potential in-use compliance concepts and approaches.
- An interim evaluation of its MHDV regulation in the 2021-2022 time period would help improve the regulation's overall effectiveness and value. The evaluation's primary focus would be on preparations for any future regulations beyond the Phase 2 standards.

# VEHICLE TECHNOLOGY PROGRESS

**Finding:** New fuel and power source options (including hybrid-electric systems and auxiliary power sources) may be needed to achieve significant further progress in reducing fuel consumption and GHG emissions from MHDVs over the next couple of decades. In addition to direct fuel consumption and emissions from the vehicle, these fuel options will likely differ significantly in upstream and non-tailpipe emissions.

**Recommendation 2-7:** NHTSA, in coordination with EPA, should evaluate and quantify the life-cycle GHG emissions and fuel consumption of all fuels and technologies whose use could contribute to meeting a third phase of standards, and take them into consideration in developing a third phase of regulation. It will be critically important to incorporate a life-cycle perspective in those instances where some fuel-technology pathways' life-cycle emissions may lead to an increase, rather than a decrease, in emissions.

# ALTERNATIVE TECHNOLOGY & APPROACHES - WHR

**Finding**: Waste-heat recovery (WHR) used in Class 8 over-the-road vehicles potentially offers significant cost-effective fuel savings. Expected progress in WHR technology suggests this technology will see increasing penetration in Class 8 combination tractors. There are many approaches to waste-heat conversion to power that can provide up to 4 percent efficiency improvements in modern truck engines.

| Category of Heat Recovery | Specific Example Technologies | Range of Efficiency Impact | Source |
|---|---|---|---|
| **Direct energy conversion** | Thermoelectric materials and devices | 1-2% in large pickup<br>~3.3% of incident energy | Liang et al. (2015), Kumar et al. (2013) |
| **Direct energy conversion, additional examples** | Thermionic, pyroelectric, thermoacoustic, usually combined with piezoelectric, thermophotovoltaic | | Hunter et al. (2011), Yu et al. (2012), Keolian (2011), Wekin (2008), Fraas et al. (2003) |
| **Mechanical recovery** | Turbocompound mechanical or electrical | 1-5% overall reduction in fuel consumption | NAS (2010), SwRI for NHTSA (2014) |
| **Heat engine cycle** | Organic Rankine cycle | 4-8% | Koeberlein (2013), SwRI-NHTSA (2014), Eaton, Singh (2011), Greszler (2012) |
| **Heat engine cycle** | Refrigeration cycle<br>Stirling engine | | Nadaf and Gangavati (2014) |
| **Thermochemical recuperation** | Fuel reforming, hydrogen production | 10-13% | Daw et al. (2010), Liang et al. (2015) |

# ALTERNATIVE TECHNOLOGY & APPROACHES - HYBRIDIZATION

**Finding**: With respect to hybridization of commercial vehicles, several international light-duty vehicle manufacturers and Tier 1 battery suppliers are projecting costs for plug-in hybrid-electric or battery electric vehicle battery packs that will achieve \$120/kWh by 2020 and \$100/kWh or less by 2025. In 2027 and beyond, stop-start technology applications are expected to have payback periods that would make them attractive in many applications to private firms.

The fuel consumption and $CO_2$ benefits that can be derived from the use of HEVs are highly dependent upon the type of vehicle, its size and weight, and, most importantly, its intended duty cycle. Use cases involving a high frequency of braking cycles, such as refuse trucks or urban buses, can gain significant benefits through regenerative braking, where the size of the energy storage system can be somewhat limited in size to recover primarily only the braking energy and then launch the vehicle.

Other applications, such as urban delivery trucks, may choose to incorporate larger energy storage systems and optimize total route operational efficiency with a combination of regenerative braking and periods of operating the ICE and higher load levels, to minimize carbon-based fuel consumption.

# ALTERNATIVE TECHNOLOGY & APPROACHES - HYBRIDIZATION

| Vehicle Class | Hybrid Type | Vehicle Use | Duty Cycle | Approx. FC Red (%) |
|---|---|---|---|---|
| Class 2b-3 | 12 V start/stop (S/S) belt-starter-generator (BSG) | Heavy-duty pickup and van | Urban + highway | 3.5 |
| Class 2b-3 | Integrated S/S with regen/launch assist | Heavy-duty pickup and van | Urban + highway | 10 |
| Class 2b-3 | Parallel strong hybrid | Heavy-duty pickup and van | Urban + highway | 20 |
| Class 4-5 | 12 V S/S BSG | Vocational vehicles | Urban + highway | 3.5 |
| Class 4-5 | Integrated S/S with regen/launch assist | Vocational vehicles | Urban + highway | 16 |
| Class 4-5 | Parallel strong hybrid | Vocational vehicles | Urban + highway | 20 |
| Class 4-5 | 12 V S/S BSG | Delivery trucks | Urban delivery | 3.5 |
| Class 4-5 | Integrated S/S with regen/launch assist | Delivery trucks | Urban delivery | 20 |
| Class 4-5 | Parallel strong hybrid | Delivery trucks | Urban delivery | 25 |
| Class 6-7 | 12 V S/S BSG | Vocational vehicles | Urban + highway | 3.5 |
| Class 6-7 | Integrated S/S with regen/launch assist | Vocational vehicles | Urban + highway | 16 |
| Class 6-7 | Parallel strong hybrid | Vocational vehicles | Urban + highway | 20 |
| Class 6-7 | 12 V S/S BSG | Delivery trucks | Urban delivery | 3.5 |
| Class 6-7 | Integrated S/S with regen/launch assist | Delivery trucks | Urban delivery | 20 |
| Class 6-7 | Parallel strong hybrid | Delivery trucks | Urban delivery | 25 |
| Class 8 | 12 V S/S BSG | Vocational refuse truck | Urban accel/brake | 3.5 |
| Class 8 | Integrated S/S with regen/launch assist | Vocational refuse truck | Urban accel/brake | 22 |
| Class 8 | Parallel strong hybrid | Vocational refuse truck | Urban accel/brake | 30 |

# ALTERNATIVE TECHNOLOGY & APPROACHES - FINDINGS

- **Petroleum-derived diesel fuel** will likely remain the dominant CI engine fuel through the time period of this study (approximately 2030). Regarding changes to diesel fuel to reduce GHG emissions, the most effective measure would be additional use of biomass-derived fuel components (in contrast to changing diesel fuel performance specifications).
- **A range of opportunities exists to improve energy efficiency and reduce GHG emissions in freight transportation** (Chapters 9 and 10). For example, modifying truck size and weight standards, facilitating intermodal shipments, and truck platooning could improve the fuel efficiency of freight shipments.
- The committee found that **higher weight limits and longer combination vehicles could significantly improve productivity** and therefore reduce the overall distance traveled in the heavy-vehicle long-haul transportation sector. In addition, the development of freight transfer facilities near urban areas would increase the use of more agile, fuel efficient, and less polluting vehicles for “last-mile” freight movements and would facilitate the early adoption of autonomous vehicles.
- **The commercialization and deployment of advanced technologies, fuels, and freight movement methods significantly different from those currently in use may need to start as early as 2030** if ambitious national GHG emissions reduction and fuel-economy goals are established for 2050.

# FUTURE REGULATORY FRAMEWORK - FINDINGS

- **Reliable Data** NHTSA and the EPA currently lack reliable data on real-world vehicles that can be used to establish a credible regulatory baseline. It is essential for evaluating the effectiveness and success of the regulatory program and identifying future regulatory priorities and directions.
- **In-Use Fuel Consumption Measurement** An effective method of determining in-use fuel consumption of trucks, and thereby of determining the overall effectiveness of the regulatory program, is not currently feasible technologically. Such a method is necessary to assess any differential between the LSFC of an individual vehicle model as certified pre-sale using simulation and the LSFC achieved by such vehicles on-the-road. The data stream this creates will allow NHTSA to identify opportunities to improve the effectiveness and reduce the cost of the program.
- **Explore In-Use Compliance** Given that NHTSA's Phase II rule covers model years through 2027, the agencies have sufficient time to explore potential in-use compliance concepts and approaches. The available time should allow stakeholder involvement in a deliberative process, prior to the issuance of any post-2027 regulations, to establish the objectives to be achieved and assess and develop an in-use compliance concept that best meets the objectives.

# FUTURE REGULATORY FRAMEWORK - RECOMMENDATIONS

**Recommendation 3-8:** NHTSA, in concert with the EPA, should commit resources to collecting real-world fuel consumption and GHG emissions data from a robust and representative sample of pre-control trucks and for each model year subject to the Phase I and II standards, with priority given to those categories of trucks with the greatest fuel consumption. These data can be used to establish a regulatory baseline that can be used to evaluate program effectiveness and future regulatory priorities.

**Recommendation 3-6:** The agencies should develop an effective in-use compliance method that would allow the overall performance of the regulatory program to be quantified, identify whether groups of in-use trucks may not be in compliance, and provide insight into truck operating conditions where fuel consumption of future trucks could be further reduced.

# Question & Answer Session