The Future of **Heavy-Duty** Powertrains

Issues, technical and financial challenges, outlook 2007 and beyond.

A unique study designed to comprehensively explore the future.

Open Summary for CLEERS

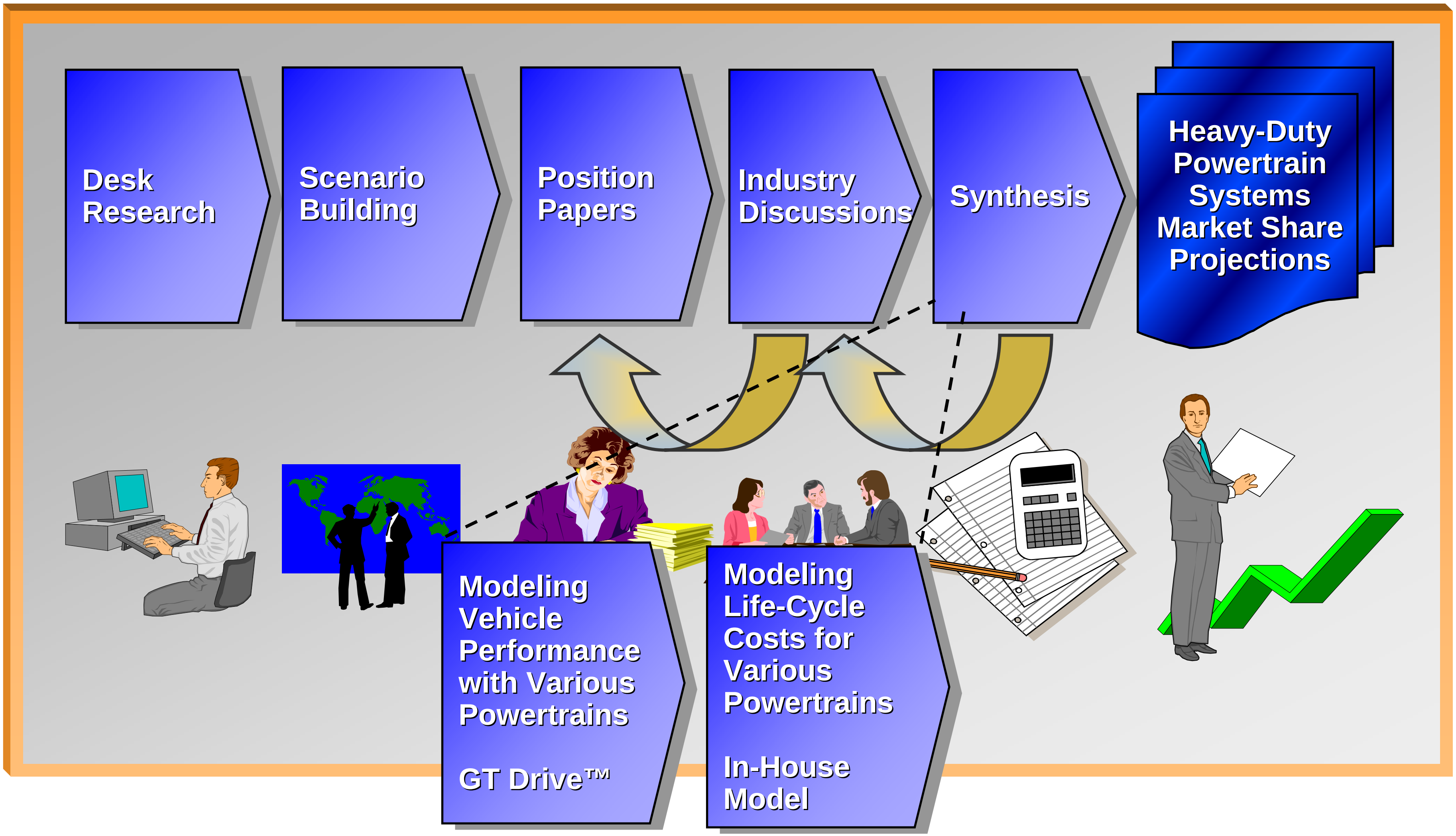
GLOBAL INSIGHT

TIAX

The scope of this study includes heavy-duty powertrain systems in Western Europe, U.S., and Japan in the 2007–2020 time frame.

- Western Europe, U.S., and Japan are technology leaders
- Years 2007 to 2020
- Primary heavy-duty (>5 t) powertrain technology areas
  - » Power units
  - » Hybrids (electric, hydraulic)
  - » Exhaust gas treatment (EGT)
  - » Transmissions
  - » Alternative fuels
- Describe each technology and its costs
- Assess market share projections under each scenario - and why?
- What is the sensitivity of these to each scenario?

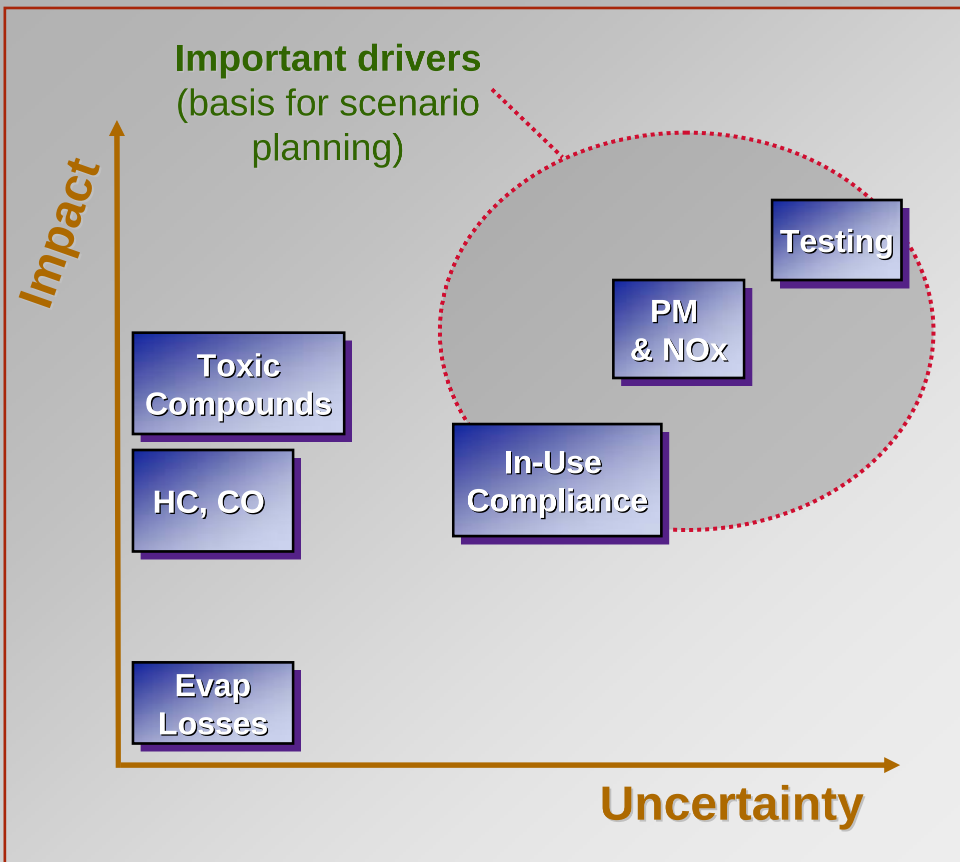
The market share projections were developed in six steps.



Three key tools were used to develop the future powertrain forecasts for each segment and region.

GT-DRIVE™	A vehicle fuel efficiency model developed by Gamma Technologies was used to estimate: • Fuel efficiencies of each vehicle segment in each geographical region • Impact on fuel economy of rolling resistance, aerodynamics, advanced IC-engines, and advanced transmissions for all segments in all three regions
Spreadsheet Model of Hybrid Benefits	A post-processing model developed to assess the impact of hybridization on fuel economy and brake savings for selected vocations
Spreadsheet Financial Model	• Determined the impact of each powertrain technology on the life-cycle costs of each on-highway truck segment in each region, considering impacts of powertrain technologies on capital costs, fuel costs, finance costs, operating and maintenance costs. • The powertrains offering the best economics for each on-highway duty cycle was forecast as the long term winner for that vocation and ramped up in accordance with the standard rate of industry technology acceptance. • Off-highway markets will follow the dominant on-highway technology

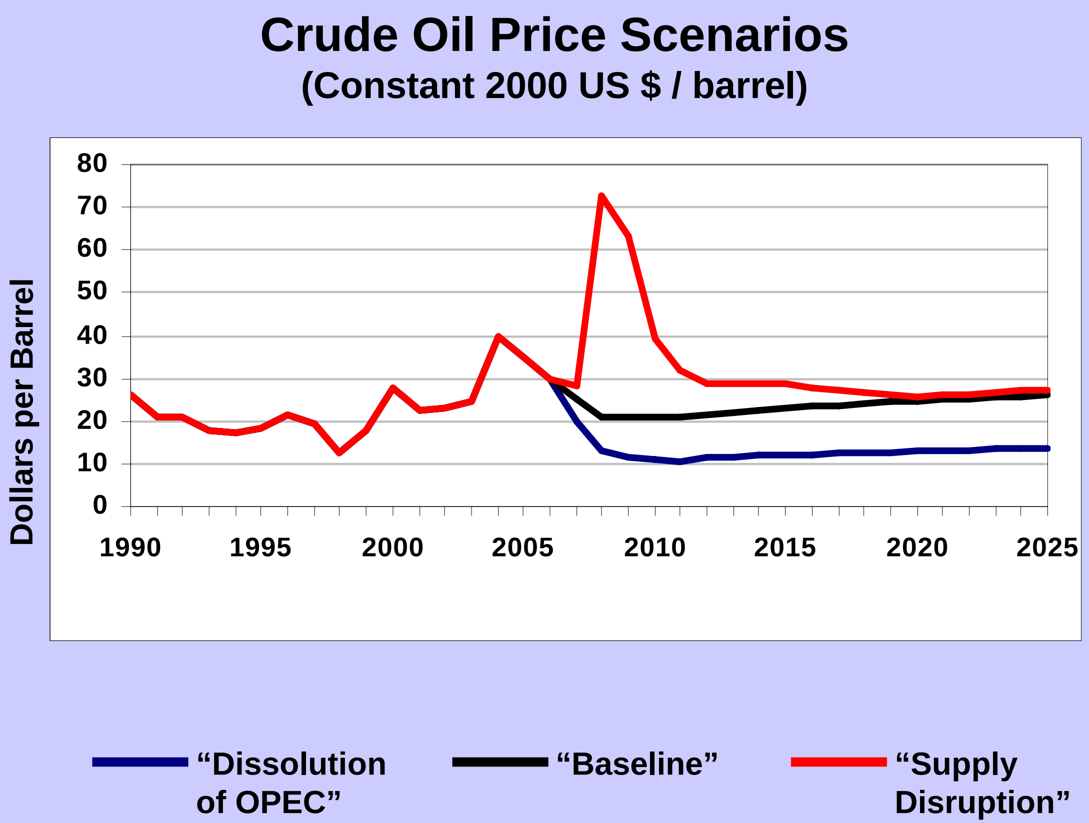
Focusing on the high-impact, high-uncertainty regulatory issues, three regulatory scenarios with varying constraints on particulate matter (PM) and NOx and/or in-use compliance were developed.



Regulatory Scenarios

- **“No Surprises” –** a “business as usual” baseline scenario
- **“Increased Compliance” –** a scenario in which the regulators are primarily concerned with maintaining the levels of emission performance of in-use vehicles to as-new levels. This is achieved by a combination of changed test methods to reflect combined engine and transmission or vehicle emissions performance at the chassis level as well as OBD/OBM
- **“Increased Standards” –** a scenario where NOx and PM emissions become the highest priority along with maintenance of in-use performance

All energy scenarios indicate a plentiful supply of petroleum and imply that alternative fuels will not be mainstream through 2020.



Note: Long-term trends as opposed to short-term fluctuations

- The "**Dissolution of OPEC**" scenario assumes the OPEC cartel, when faced with shrinking market share and weak demand succumbs, to internal disagreements.
- The "**Baseline**" scenario assumes that OPEC maintains a cohesive organization that manages the world's supply of crude oil within an agreed-upon price boundary.
- The "**Supply Disruption**" scenario assumes a war in the Middle East constrains supply, pushing prices up until alternative fuel sources or oil transport modes are developed.

Three major scenarios bound the plausible future.

Future Scenarios	"Easy Street" (Less Probable)	"Baseline" Most Probable)	"Rough Ride" (Least Probable)
Environmental Regulation Scenarios	"Increased Compliance" (OBD/OBM)	"No Surprise" (Current Outlook)	"Increased Standards" (Tougher Standards)
Oil/Energy Price & Availability Scenarios	"Dissolution of OPEC" (Low Price/ Plentiful Supply)	"Baseline" Oil Price/Availability Scenario	"Supply Disruption" (High Price)

Output for Each Scenario

- **Regulatory constraints:**
  - HC
  - NOx
  - PM
  - In-use performance monitoring
  - Engine/transmission or chassis testing
- **Fuel Prices**

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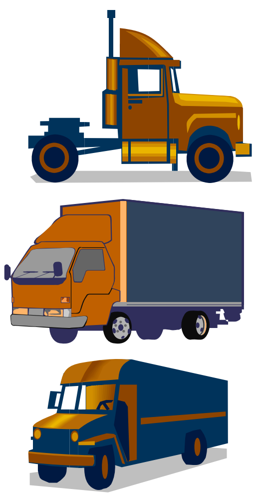
Two key sub-systems:

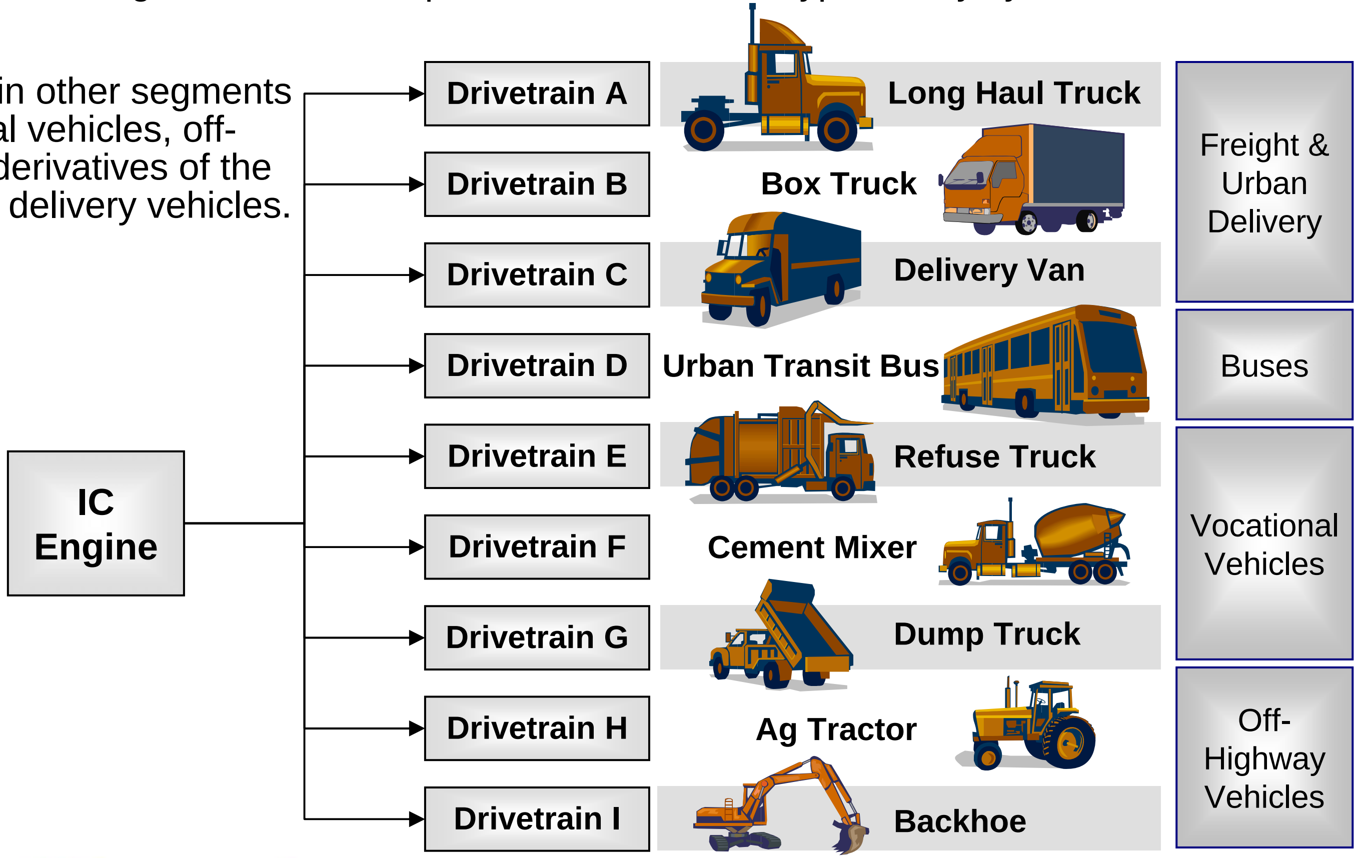
Power Unit

- IC engine technologies are driven primarily by the largest segments: on-highway long haul freight and urban delivery.
- IC engines used in other segments (buses, vocational vehicles, off-highway) will be derivatives of the freight and urban delivery vehicles.



Drivetrain

Drivetrain technologies (transmission and hybridization) are tailored for the different vehicle classes to optimize performance over the typical duty cycle.



Eleven steps yield key findings and conclusions --

1. Define vehicle categories to be analyzed
2. Identify representative vehicles for each category in each region
3. Identify representative duty cycles for each vehicle category and each region
4. Develop financial model for each vehicle category, each scenario and each region
5. Develop vehicle simulation model for key vehicle categories in each region
6. Identify MY 2020 competing IC engine technologies
7. Exercise vehicle simulation model for candidate IC engine technologies to assess fuel consumption and amount of EGT reagent needed
8. Employ financial model to compare life-cycle cost for the candidate IC engine technologies for each on-highway vehicle category and each region
9. Identify the most attractive (i.e., optimum economics and manageable technical risk) IC engine and EGT technology combination for the on-highway vehicle categories
10. Explore the attractiveness of transmission upgrades / substitution for each on-highway, bus, and vocational vehicle category in each region
11. Assess the potential and attractiveness for hybridization in selected vehicle categories in each region

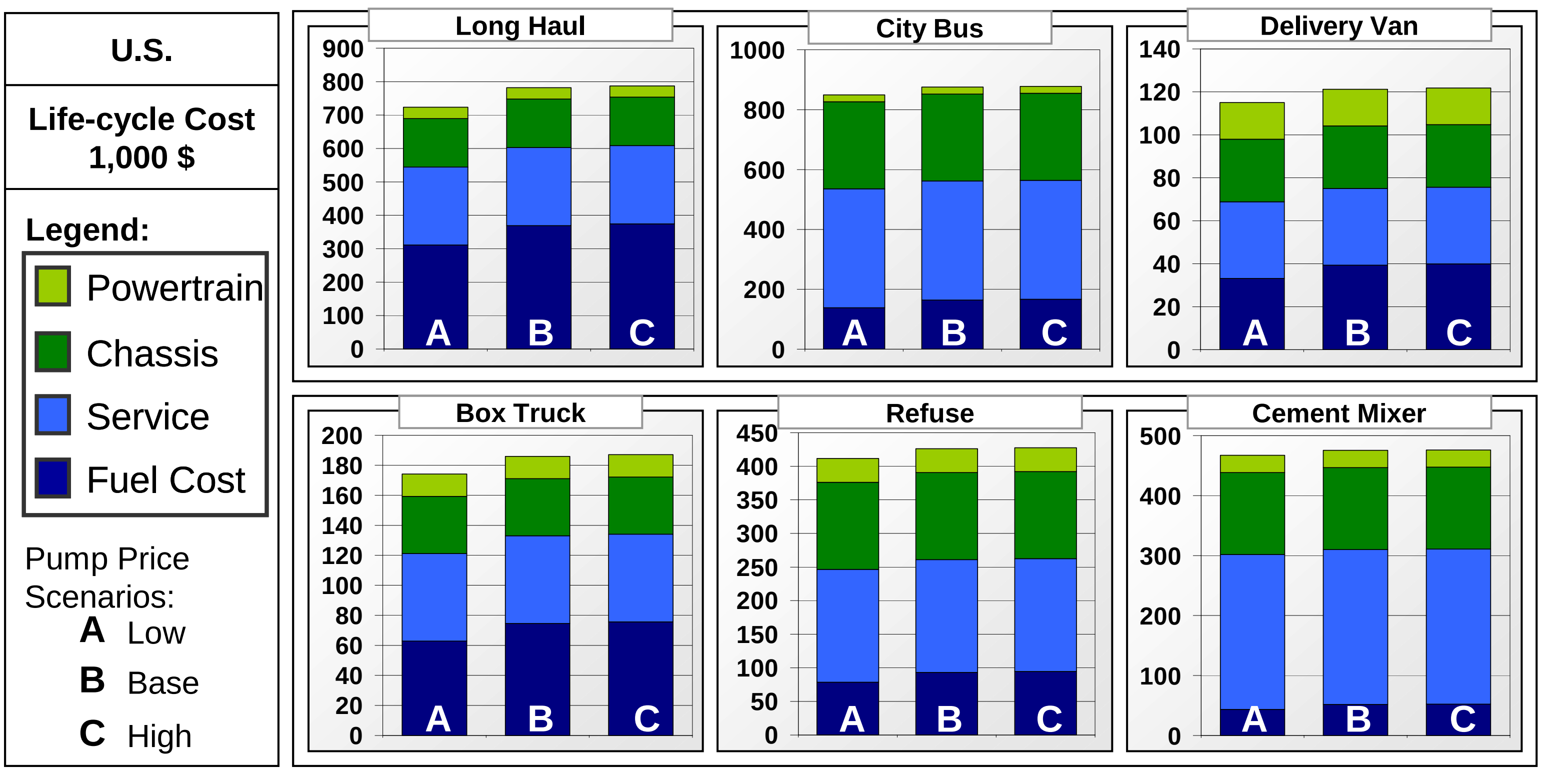
Promising future technologies will continue to be promising ...

In other words, many technologies capture the imagination of the public, governments and even industry, but few are serious solutions to the challenges of the next 2 decades, including…

- **Continuous combustion**
  - » Stirling engine
  - » Gas turbines
  - » Steam engines
- **Alternative configuration**
  - » Wankel
  - » Scotch yoke
  - » etc.
- **And except for niche applications:**
  - » Fuel cells (demonstration fleets or APU)
  - » Battery electric
  - » Alternative fuels

Financial modeling shows that in the largest segments, fuel and service drives life-cycle cost in all three 2020 scenarios (U.S. shown)

- Given the crucial importance of fuel cost, the fuel consumption impact of competing IC engine technologies were assessed by computer simulation (GT-Drive™).
- In sharp contrast, powertrain capital cost is not critical to the life-cycle cost – it is included in the analysis but does not deserve the same amount of attention as fuel economy.
- In the start-stop segments (bus, delivery and refuse), service cost dominates, which in turn is driven by brake maintenance; this presents a business opportunity for hybridization.



2020 powertrain specific cost assumptions: (1) CIDI + Manual Transmission; $60/kW, (2) CIDI + Automatic Transmission; $75/kW

All three diesel engine technologies will compete for market share as the industry makes the transition to full-mode HCCI.

Engine Type	What It Is	Key Features
Three Compression Ignition Diesel-Fueled Contenders		
CIDI (MY 2020)	This is the baseline engine, representing a progressive evolution of today's CIDI engine.	Ongoing refinements in the areas of fuel injection, air management, advanced controls, and variable valve timing will enable a continuation of the historical rate of fuel efficiency and emissions improvement. Fuel efficiency is expected to improve by 3% over the next 15 years, and NOx emissions by 10%.
Advanced CIDI	Electric turbocompounding is a key feature of the advanced CIDI.	Electric turbocompounding and electric torque assist via a starter-alternator will help improve the fuel economy by 1-5% over typical drive cycles. NOx emissions are similar to the 2020 CIDI engine.
Mixed-Mode HCCI	Based on the advanced CIDI, and with HCCI operation at loads below 10 bar BMEP (i.e., 50% load and lower).	Virtually zero engine-out NOx emissions when in HCCI-mode (which is most of the time for typical drive cycles). Fuel efficiency is similar to the 2020 CIDI engine.
Otto Engine Being Used in CNG Applications		
HD Otto possible for niche applications e.g. CNG	This is a turbocharged stoichiometric Otto engine with electric turbocompounding and intake valve throttling.	The heavy-duty Otto engine is a light-fuel flame propagation engine. Tailpipe emissions can be nearly eliminated by the use of affordable TWCs. Fuel economy will suffer significantly however, and even more so will well-to-wheels CO_2 emissions.

All engine types will continue to compete in the foreseeable future, but the transition to full-mode HCCI is virtually inevitable.

Engine Market Shares: All Scenarios

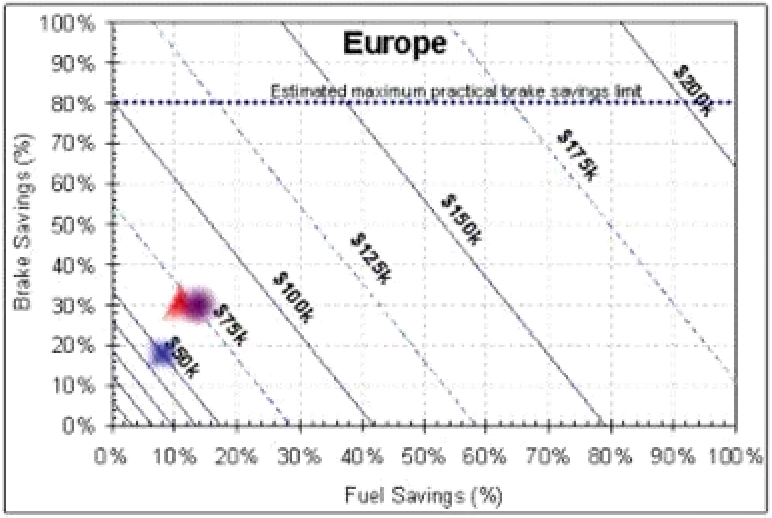
Engine	2007	2010	2015	2020
Conventional CIDI	85%	75%	50%	30%
Advanced CIDI	5%	15%	35%	25%
MM HCCI	<5%	<5%	10%	15%
HCCI	0%	0%	0%	25%
SI	5-10%	5-10%	5-10%	5-10%

NOTE:

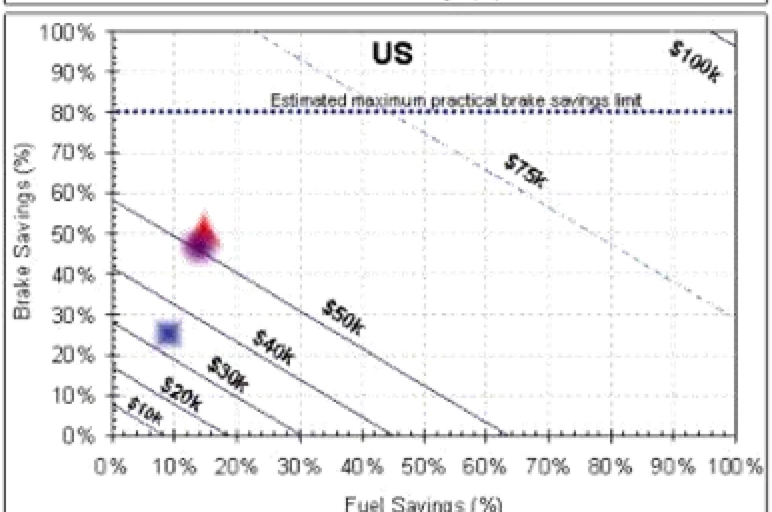
MM HCCI = Mixed-mode HCCI

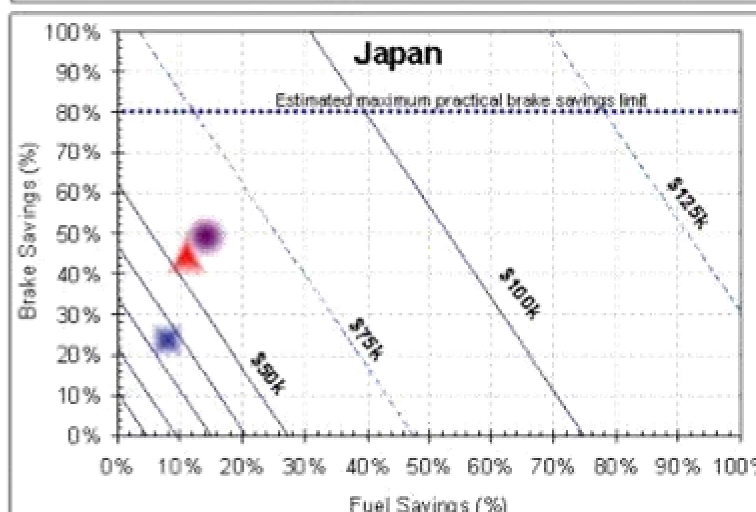
HCCI = Full-mode HCCI

Analysis of the commercial viability of hybrids must include brake savings.



- Energy storage capacity significantly influences brake service savings much more dramatically than fuel savings due to the higher monetary value of the energy (on a per kW basis) (i.e., the cost of brake wear and associated maintenance per kW absorbed is greater than the energy released by the fuel).





The IC engine will remain the dominant prime mover through 2020 (and beyond!).

- **Even under the "Increased Standards" scenario, several competing approaches to EGT have very high probabilities of success, enabling diesel engines to meet future standards.**
- **At the same time, the diesel engine is rapidly evolving towards HCCI combustion, reducing the challenge presented to the EGT system.**
- **HCCI combustion is clearly the long-term winning engine technology.**
  - » Life-cycle costs are reduced
  - » Inherently robust emission control ensures in-use compliance
  - » Will likely drive the use of self-shifting transmissions to keep the engine in the HCCI operating range
- **Electric turbocompounding will likely be universally used in all diesel engines but the conventional CIDI.**

Our conclusions point to the instrumental but temporary importance of exhaust gas treatment for future heavy-duty powertrain.

- **By 2010, exhaust gas treatment for NOx reduction will be required.**
  - Competing NOx reduction systems are too close to call with certainty based solely on technical merits in the medium term.
  - Western Europe and some individual OEMs have already made the decision to go with urea-based SCR in the short term.
  - We expect that the U.S. and Japan will go with NOx traps in the medium term
- **After 2010, HCCI development will enable more and more of the duty cycle to be driven with sufficiently low NOx and PM to obviate the need for EGT.**
  - » As long as the engine can move into the diesel mode, lean NOx and PM EGT will be required.
  - » If diesel operation can be avoided via HCCI, the need for lean NOx and PM EGT could be eliminated.
    - This would eventually make obsolete any investment in reagent support infrastructure made in the 2004 –2010 time period.
    - Any reagent infrastructure put in place will have a very long but steadily declining “tail”, as it must remain in place to service the in-use fleet.

The complete study includes:

- ✓ Independent assessments of the Heavy Duty (~ 5 tons and above) vehicle powertrain technology trends against which to compare your own investments and strategies.
- ✓ The sensitivity or robustness of certain technologies to different alternative futures.
- ✓ Insights into possible business or technical threats and opportunities associated with future heavy vehicle powertrain (including exhaust gas treatment) technologies.
- ✓ Indications of end-user benefits associated with different powertrain technology choices.
- ✓ An understanding of possible alternative futures

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