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Developing Environmentally Friendly Motor Vehicle Technologies Eyeing 2020 and Beyond

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Ultimately stringent emission regulations will be imposed on gasoline and diesel vehicles between 2010 and 2016 in Japan, the USA and the EU. To comply with these regulations, automakers are being forced to develop ultra low-emission engine systems by optimizing combinations of technologies related to combustion, aftertreatment and fuels. These vehicles are expected to retain their positions as state of the art technologies for two decades to come. Toward 2020 and beyond, more emphasis will be placed on improvements in fuel economy and the use of renewable energy and fuels such as electricity and biofuels to reduce oil dependence in the transportation sector, thereby mitigating global warming. Thus, the hybrid vehicle is a very promising alternative option for significantly improving fuel efficiency, followed by the electric vehicle. Cost-effective permanent magnetic motors, lithium-ion batteries and electric and electronic devices are essential for these vehicles. The use of advanced lightweight materials will also be more important to reduce energy consumption for all vehicle categories. The materials include high-tensile steel, light metals and plastics. Fuel cell vehicle technologies, however, must overcome many difficult and uncertain issues based on fundamental research despite their favorable features and deserve fundamental research. These advanced environmentally friendly vehicle technologies should properly be shared among motored and motorizing countries from the viewpoint of global environment.

Keywords: *Internal combustion engine, Hybrid vehicle, Electric vehicle, Light weight materials*

1. Introduction

Developed countries are planning more stringent regulations on motor vehicle exhaust emissions and on fuel efficiency to come into effect in 2010 to 2015 and later, respectively. They are aimed at reducing urban air pollution, saving oil and mitigating global warming. Increases in oil prices will be caused by greater demand for oil in developing and motorizing countries as well as by instability associated with oil production and supply in oil exporting countries. Automobile and related industries are now facing a situation of having to achieve both low exhaust emissions and high fuel efficiency at the same time. They are therefore being forced to engage in severe competition in the field of technological development not only to survive in the international market but also to make contributions to global warming mitigation. This paper is intended to describe the present status and future perspectives with regard to environmental and energy issues of technological development in the automobile industry, and also includes the personal opinions of the author.

2. Future Gasoline and Diesel vehicles

2.1 Emissions reduction technologies

(1) Gasoline vehicles

In Japan, new long-term vehicle emission standards have been in effect since 2005, and the post new long-term standards started in 2009 for both gasoline engine and diesel vehicles. NOx and hydrocarbon (HC) emissions in gasoline vehicles have been reduced eventually to less than 1% of the levels that existed in 1972 before controls were first imposed. The present standards are very stringent to be applied in Japan, the EU and the USA, and the technology for controlling gasoline vehicle emissions has thus been making significant progress recently. Improvements in the performance of electronically controlled fuel injection systems and three-way catalysts for the aftertreatment of emissions have contributed significantly to this progress. In Japan, low-emission vehicle standards set lower emission levels for NOx and HC. Tax incentives are provided to encourage customers to select LEVs, thereby promoting the development of these vehicles by automakers. Substantially, almost all gasoline vehicles are certificated as LEV or Ultra-LEV reducing NOx and HC regulation levels by 50% and 75%, respectively thanks to the gasoline engine emission control measures explained above.

(2) Diesel vehicles

On the other hand, diesel engines, which are used in a wide range of vehicle categories from passenger cars to buses and trucks, achieve 20% to 30% higher fuel efficiency than gasoline engines, and therefore have the potential to control CO_2 emissions. However, the inherent diffusion combustion characteristics of diesel engines cause high emissions of both NOx and PM (particulate matter). For this reason, the air pollution effect of diesel engines is actually more critical than that of gasoline engines. This situation has resulted in a strengthening of the NOx and PM regulations imposed on diesel vehicles.

Figure 1 compare standards for heavy-duty diesel vehicles with a gross weight of more than 3.5 tons in Japan, the US and the EU. A simultaneous reduction in both PM and NOx is extremely difficult to achieve because a trade-off relationship between these two types of emissions is inevitable. Future regulations in Japan, the USA and the EU have set very severe target values that are comparable to those for gasoline engines, taking different test cycles. Thus, the world-harmonized test cycle (WHTC) are now being discussed for heavy-duty diesel vehicle emissions under the WP29, GPRE of the United Nations to reduce vehicle development costs and time by removing technical barriers across countries [1].

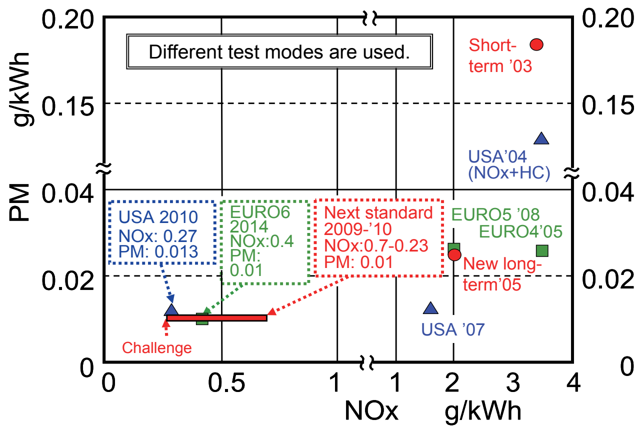

Figure 1: Heavy-duty Diesel Vehicle Emissions Standards in Japan, the EU and the USA

Figure 2 illustrates typical combined emissions reduction technologies that may be of practical use to comply with these severe regulations. Such emissions reduction systems necessitate an intercooled turbocharger, an electronically controlled high-pressure fuel injection system and an EGR (exhaust gas recirculation) system as well as various aftertreatment systems. The injection system, typically a common rail system, can provide high injection pressures up to 240 MPa, creating multiple injection patterns to enable very lean premixed charge compression ignition (PCCI) combustion to simultaneously reduce NOx and PM emissions to extremely low levels, thereby minimizing the fuel penalty and lightening the dependence on emissions aftertreatment. However, PCCI operation is limited to the low and medium load ranges to avoid explosive premixed combustion in spite of many experimental and numerical studies conducted on this combustion phenomena and control.

Key aftertreatment technologies include DPF (diesel particulate filters for capturing PM)

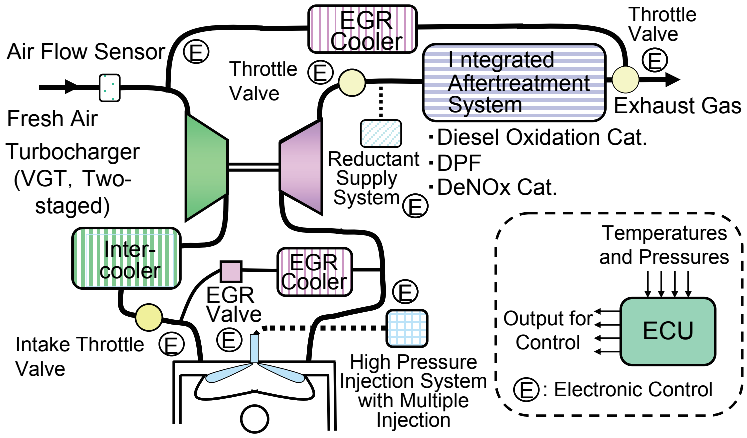

Figure 2: Typical Advanced Diesel Emission Control System

systems, and deNOx catalyst systems such as the selective catalytic reduction (SCR) system that uses a urea-water solution as the NOx reduction agent and the NOx storage reduction (NSR) catalyst system that employs an additional rich spike of fuel supply to reduce stored NOx.

Eventually, developing countries will be enforced to follow the similar levels with the developed countries' standards to improve air quality in motorizing cities.

2.2 Fuel efficiency improvement technologies

Figure 3 compares actual and projected green house gas emissions for new passenger vehicles by country and region in 2002 to 2022 which are directly associated with fuel economy standards imposed on passenger vehicles. Japanese automakers have achieved the 2010 target five to six years early. The next fuel economy targets are supposed to be in effect in 2015, with an average improvement of more than 20% compared to the 2010 targets expected. In the EU, a voluntary program was planned to be started by the auto industry in 2008, which set a fuel economy target equivalent to 140 g-CO_2/km. However, since this target could not be achieved, it will compulsorily be reduced to 130 g-CO_2/km in 2012 to 2015. The US will also tighten fuel economy standards for passenger and light-duty vehicles as well.

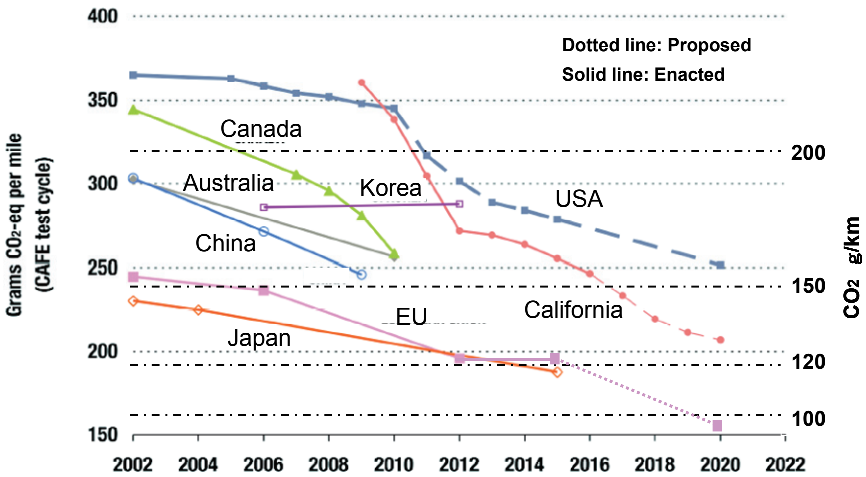

Figure 3: Actual and projected green house gas emissions for new passenger vehicles by country/region in 2002 to 2022 (Source: International Council on Clean Transportation)

On the other hand, heavy-duty vehicles that use diesel engines mainly have not been subject to fuel efficiency regulations because improvements in their fuel efficiency are likely to be promoted by the market from the viewpoint of fuel economy. In Japan, however, fuel economy standards have been set to be in effect in 2015 for heavy-duty diesel vehicles to reduce fuel consumption and CO_2 emissions, requiring a 12.2% fuel economy improvement compared to 2002 levels on vehicle weight and number average basis.

Table 1 shows fuel efficiency improvement technologies that are used at the present time or will be introduced in the near future. With gasoline vehicles, direct-injection engine, CVT (continuously variable transmission), and variable intake/valve mechanism technologies are especially efficient and will achieve further market expansion in the future. Moreover, fuel ecomomy improvement technologies include such important concepts as reducing vehicle weight, air drag and rolling resistance as will be mentioned later.

On the other hand, with smaller diesel engines, the use of direct fuel injection and turbocharging has also been increasing to improve fuel economy and reduce CO_2 emissions as well as to increase power output. The market share of direct-injection diesel passenger cars has reached about 50% in the EU. However, they will have to deal with the further strengthening of emissions standards in the future, from EURO5 to EURO6, by applying not only DPFs but also deNOx catalysts.

Table 1: Technologies for Improving Fuel Economy

(Improvement ◎: >10% ○: 5-10% □: <5%
G: Gasoline vehicle, D: Diesel vehicle)

Items		Technologies
Engine	New concept	◎Direct-injection ◎Hybridization ◎Miller cycle ○Lean burn(G)
	Control	○Stopping engine at idle □Precise fueling and ignition timing
	Mechanism	□Variable Intake/Valves（SCV, VVT） ○Modulated displacement(G) □Four valves ◎Engine downsizing ○Variable geometry turbocharging(D)
	Friction reduction	□Improving lubrication □Lightweight moving parts
Drivetrain		○CVT ○Automated MT □Lockup mechanism
Vehicle body		◎Lightweight materials ◎Low air drag □Low rolling resistance tires

2.3 Gasoline, diesel fuel and their alternatives

Low sulfur fuels are essential to help maintain the performance of the aftertreatment systems explained above. In Japan, the sulfur content of diesel fuels has been reduced from 50 ppm to 10 ppm since 2005 by means of deep desulfurization technologies in oil refinery processes. Following Japan, such almost sulfur-free fuels are also marketed in the USA and the EU.

Biomass fuels including bioethanol and biodiesel have high compatibility with gasoline and diesel fuel, respectively. Biomass-to-liquid fuels can be produced for diesel fuel and possibly for gasoline by means of Fischer-Tropsch's synthesis method using gasified biomass including agricultural products and their wastes. All these biomass fuels have high compatibility with present oil, meeting the convenience requirements of fuel suppliers, automakers, customers and fuel policy makers. In Japan, the use of gasoline blended with 3% ethanol (E3) is allowed while discussion is being conducted on blending with 7% ETBE (ethyl tert-butyl ether) produced from bioethanol and iso-butane. Gasoline with 10% ethanol is expected to be introduced after 2010. Diesel fuel is allowed to be blended with up to 5% fatty acid methyl ether (FAME or bio-diesel, produced from vegetable oil, waste cooking oil, etc.).

These biomass fuels are now only supplemental oil replacements due to limited production and supply in Japan. Careful comparisons should be made based on well-to-wheel efficiency (the overall efficiency of the raw materials to be used to drive the wheels) analysis, taking into account environmental and energy sustainability, convenience, and economy, which will increasingly lead to the replacement of oil with more favorable renewables. Attention should also be paid to avoid conflict with food production and change in land use. Such discussions should be made based on an international consensus from the viewpoint of global warming mitigation.

As described above, it is clear that gasoline engine vehicles and diesel engine vehicles must improve fuel efficiency and reduce exhaust emissions, respectively. As illustrated in Figure 4, solutions to the above problems depend on how the related component technologies can effectively be systemized, based on optimum combinations of combustion, aftertreatment and fuel technologies.

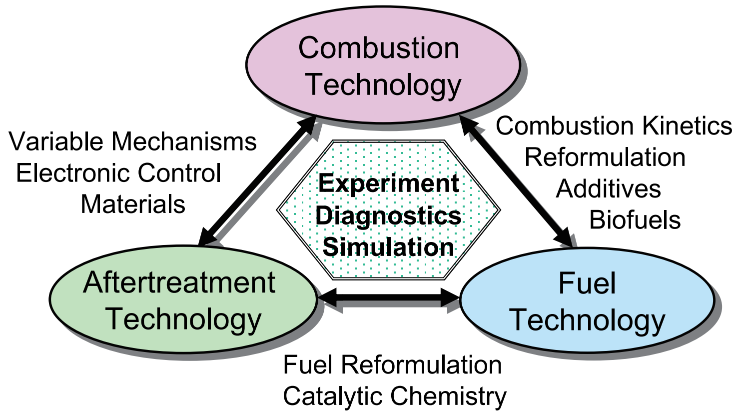

Figure 4: Three Key Technologies for Improving Emissions and Efficiency in SI and Diesel Engines

3. Development of Advanced Alternative Vehicles

3.1 Hybrid and electric vehicles

Hybrid passenger cars have the potential to significantly improve fuel economy. In the US, California's Low Emission Vehicle Program has not been successful in extending the market for electric vehicles, which were classified as Zero Emission Vehicles (ZEVs). Electric vehicles were expected to be the most promising zero emission vehicles; however, market acceptance has been unimpressive due to heavy battery weights, high costs, short ranges per full recharging, and long recharging time. The program has been revised, extending the low and zero emission vehicle categories [2]. For these reasons, the author proposes that electric vehicles should be made smaller, carrying a smaller battery unit for urban or short distance trips to significantly reduce energy consumption. In 2009 and 2010, Mitsubishi and Nissan launched small EVs, “iMiEV” and “Leaf”, respectively. Their drive rage is about 160 km, by utilizing newly developed lithium-ion battery units.

Based on the current situation, it is predictable that future developments will advance toward new hybrid vehicles and fuel cell vehicles for longer travels and electric vehicles for shorter drives by overcoming the disadvantages with earlier electric vehicles. At the same time, component technologies created through development of electric vehicles, such as advanced motor, battery and control systems, will be utilized [3].

Hybrid vehicles are powered by a combination of an internal combustion engine system and an electric motor/battery system. As shown in Figure 5, there are different hybrid types. The hybrid vehicle has the potential for improving overall fuel efficiency when the engine and electric motor are

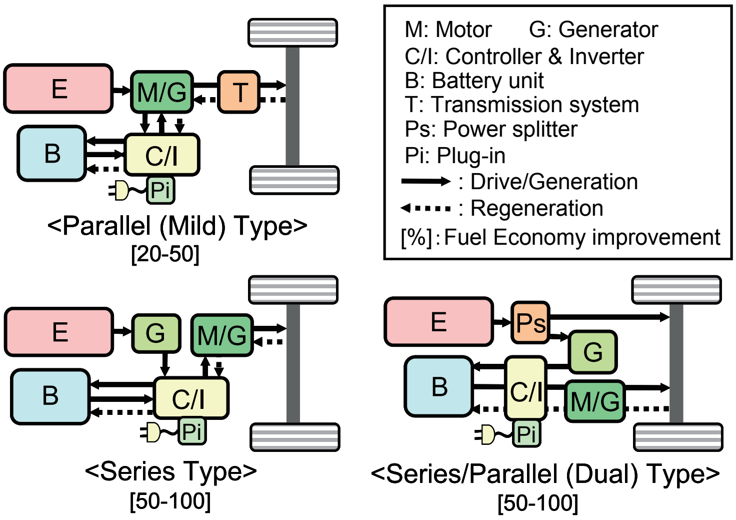

Figure 5: Three Hybrid Systems

used in their most efficient operating regions (i.e., when the engine is used at high load, and the electric motor is used at low-load and for power assistance). The ability to utilize regenerative braking by using the motor as a generator during deceleration and then storing the generated electricity in the battery is another advantage that cannot be obtained from a simple engine system, and which makes a significant contribution to improving energy efficiency in all electrified vehicles.

Recent significant developments include nickel metal-hydride and lithium-ion batteries, inverter controlled permanent magnetic synchronous motors, electronic control systems and lightweight materials. In 1997, Toyota released the Prius, the world's first mass-produced hybrid passenger vehicle. The present version's fuel economy is 38 km/liter based on the Japanese test cycle, 10-15 mode, almost twice that of other vehicles in the same class. The power system mechanism of the Prius utilizes series/parallel system as illustrated in Figure 5. Since that time, the Prius has been followed by Honda's Insight and CR-Z using a parallel hybrid system and other Toyota's hybrids. Hybrid trucks and buses have also been developed and marketed globally although their market share is still small.

Recently, plug-in hybrid vehicles are being developed and tested to utilize electricity stored in larger battery units, thereby reducing oil consumption. Battery capacity should be carefully determined for such vehicles, taking into account incremental vehicle weight and costs and economical benefits brought by cheaper electricity prices.

Figure 6 shows the example of a hybrid vehicle developed by a team including the author [4].

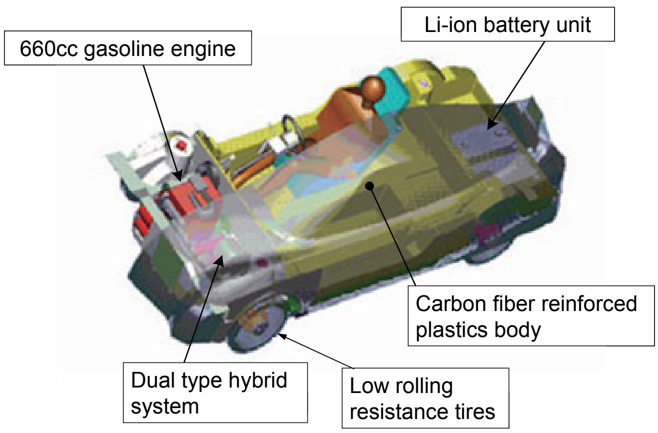

Figure 6: “Waseda Future Vehicle”

The purpose of this project was to establish a numerical model that can be used to predict hybrid vehicle performance and to optimize hybrid system control. CFRP (carbon fiber rein-forced plastic) was utilized to drastically reduce the vehicle weight to as low as 740 kg for a series/parallel type, two-passenger hybrid vehicle powered by a 0.66 L compact gasoline engine. This hybrid system has achieved a fuel consumption of 34 km/liter (10-15 mode testing). According to the author's experiences with hybrid vehicles, it will be possible to further improve the fuel efficiency of hybrid vehicles by optimizing their controls depending on driving conditions, as well as by improving the performance of associated key components.

At the same time, it is also required to minimize incremental costs by reducing the price of key components, which are about 10% to 20% higher than for other vehicles of the same class. In this way, users may benefit from the overall economical advantages resulting from higher fuel efficiency.

Let’s us go back to 1990s. A project led by America's Big 3 automakers, associated firms and universities that started in 1993 attracted attention [5]. This project, known as PNGV (Partnership for a New Generation of Vehicles), was based on an industry-government-university collaboration sponsored by the US Federal Government. The project set itself the target of achieving an ultra low fuel consumption of 80 miles/gallon (34 km/liter) for passenger cars and planned to release mass-production prototypes in 2004. To achieve this target, all the candidate vehicles adopted the parallel hybrid system using a diesel engine. However, it was found that it was difficult for diesel engines to meet the severe emissions regulations that had been introduced subsequent to the start of the project. In fact, seriously motivated by this project, Japanese automakers developed hybrid vehicles such as the Prius and Insight and released them onto the U.S. market. The project was eventually discontinued in January 2002. It has been succeeded by the "FreedomCAR and Fuel Partnership" program, which targets the field of fuel cell vehicles and hydrogen infrastructure [6].

3.2 Fuel cell vehicles

Many people consider that the fuel cell vehicle should be recognized as the ultimate electric vehicle by featuring zero emissions. This opinion results from its use of a power generation system based on the electro-chemical reactions that occur between hydrogen and oxygen. It has the potential to achieve an efficiency level as high as 50% to 60%, which is higher than hybrid vehicles.

Another merit of this system is that hydrogen can be produced conveniently from a large variety of post-oil renewable resources, including solar energy, wind power, biomass, waste and other sources. Nevertheless, in its present form, hydrogen for use in a fuel cell must still be provided mainly from fossil resources and there are many extremely difficult issues to be resolved. A comparative evaluation of the CO_2 emissions of conventional vehicles with those of hybrid vehicles, a comprehensive study into the availability of renewable fuels, and the securing of reliability and durability requirements for fuel cell systems must be carried out.

Under these circumstances, the State of California has been conducted on-road vehicle tests [6] and the US government started the FreedomCAR and Fuel Partnership [7]. In Japan, "JHFC: Japan Hydrogen and Fuel Cell Demonstration Project" was initiated in 2002. In this project, ten hydrogen supply stations have been built, and on-road demonstration tests are being conducted using about 40 passenger cars and buses. The results of this project are widely announced [8]. Even though these activities have indicated and will clarify many specific favorable features of fuel cell vehicles, its related technologies and situations now face many difficult and uncertain issues associated with costs, performance, durability, well-to-wheel environmental impacts, and hydrogen storage and fueling infrastructure, etc. As a result, the prevailing view is that real progress in the marketing of fuel cell vehicles will take possibly two to three decades more.

3.3 Lightweighting the vehicle

Major factors influencing the fuel economy include rolling resistance, air drag resistance and acceleration resistance or vehicle’s inertia force. Figure 7 shows percent distributions of energy

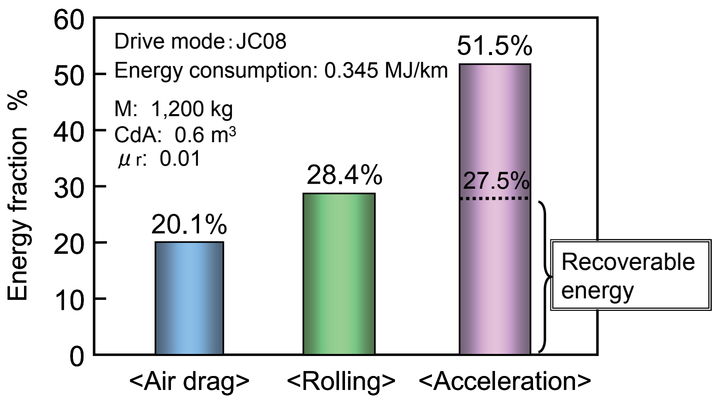

Figure 7: Consumed Energy Fraction at JC08 Mode (Y. Daisho)

required for a typical passenger car running on Japanese vehicle test mode, JC08 composed of suburban, urban and highway drive patterns. As can be seen from this figure, moving energy accounts for about 50% of the total energy consumption. Some portion of moving energy can be recovered or regenerated by means of a generator used in the electrified vehicle, thereby reducing energy consumption. It is evident from Figure 8 that lightweighting the vehicle is the most effective vehicular measure to reduce energy consumption for all vehicles categories.

Lightweight materials for the vehicle include high-tensile steel, plastics and light metals such as aluminum and magnesium alloys. It is essential to optimize the use of such different materials in designing the vehicle structure and components, taking into account their inherent mechanical properties, cost benefits, safety and recycleability. For example, a worldwide research and development activity named "WorldAutoSteel" is a significant challenge to drastically reduce the vehicle weight by using high strength steel for hybrid, electric and fuel cell vehicles [9]. The program's target is to achieve 35% body weight reduction beyond 2020 compared to 2001-2008 models, taking into account future requirements for vehicle safety and performance. Other lightweight materials are expected to be used, ranging from body parts to electric and electronic components.

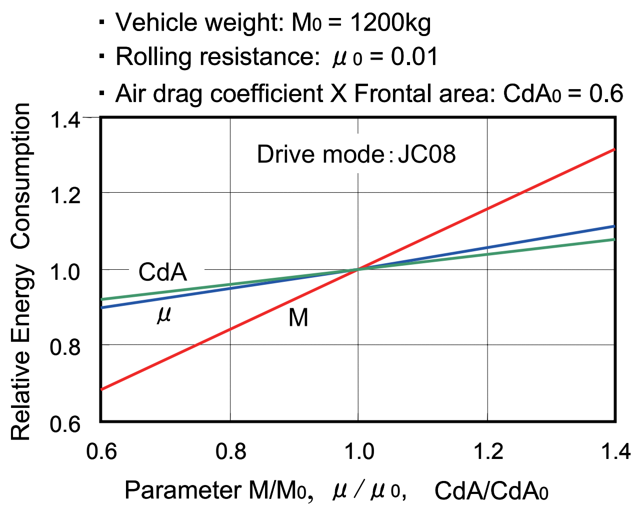

Figure 8: Relative Energy Consumption in a Passenger Car (Y. Daisho)

4. Summary

As developed countries have already set frameworks for strengthening their vehicle emissions and fuel economy regulations in the future, the automobile is now entering an era of diversification and reformation. Both gasoline engine and diesel engine vehicles will optimize combinations of technologies related to combustion, aftertreatment and fuel by setting improvements in fuel efficiency and reductions in exhaust emissions as priority targets. These vehicles are expected to retain their positions as state of the art technologies for two decades to come.

On the other hand, now is the time to attempt a transition to new concepts of vehicle systems, such as hybrid, plug-in hybrid, electric and fuel cell vehicles that achieve higher fuel efficiency than gasoline and diesel engine vehicles. Figure 9 shows possible sources and products related to fuels and energy for future vehicles. If such attempts are made, it is expected that the selection of better power systems and fuels will begin some time beyond 2020. Figure 10 compares CO_2 reduction technologies for passenger vehicles in 2020-2030 on the reference basis of a typical present gasoline vehicle. Further CO_2 reduction will necessitate the use of hybrid systems, electricity, lightweight materials and biofuels beyond 2020.

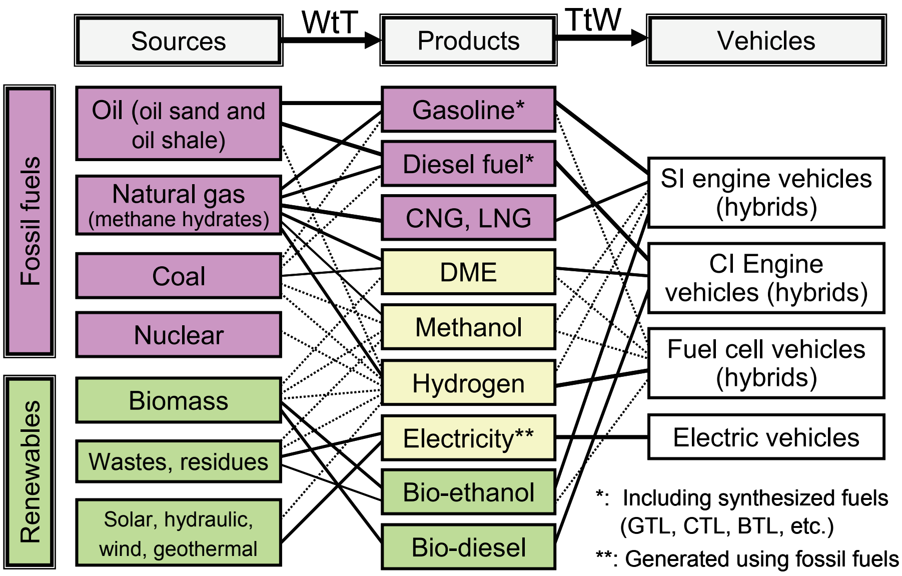

Figure 9: Sources and Products for Future Vehicle Fuels and Energy (Y. Daisho)

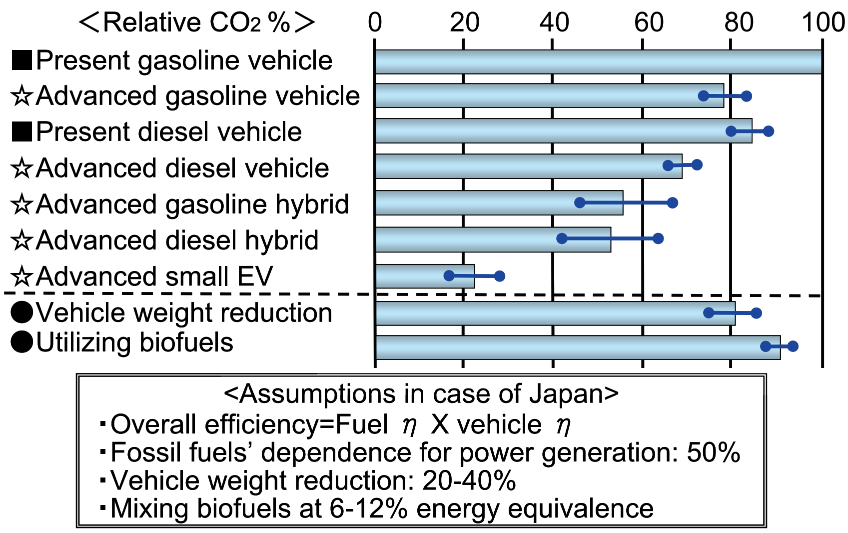

Figure 10: CO_2 Reduction Technologies for Passenger Cars in 2020-2030
-Baseline: Present gasoline vehicle- (Y.Daisho)

As illustrated in Figure 11, it is essential to overcome the issue of air pollution caused by vehicle emissions in both motorized and motorizing countries. It is also very important to change the way we use the automobile for sustainable transportation, utilizing advanced intelligent transport systems (ITS), shifting to high efficiency railways systems, providing tax incentives, planning low-carbon compact cities, etc. In the longer term, technical developments should emphasize a reduction in CO_2 emissions, efficient utilization of fossil resources, and the use of alternative fuels and energy. It should be noted that, in the near future, oil will inevitably cease to be available in sufficient quantities and will also become prohibitively priced and that above advanced vehicle technologies, fuels and energy and long-term associated policies [10,11] should properly be shared among motored and motorizing countries from the viewpoint of global environment.

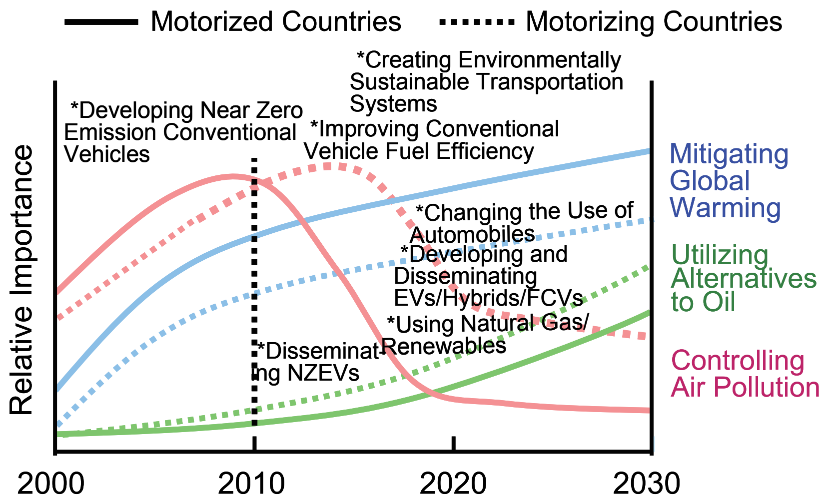

Figure 11: Relative Importance of Policy and R&D for Future Vehicles and Fuels (Y. Daisho)

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