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Vehicle Propulsion Systems

Introduction to Modeling and Optimization

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– Second Edition –

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Preface

Who should read this text?

This text is intended for persons interested in the analysis and optimization of vehicle propulsion systems. Its focus lies on the control-oriented mathematical description of the physical processes and on the model-based optimization of the system structure and of the supervisory control algorithms.

This text has evolved from a lecture series held during the last years in the mechanical engineering department at the Swiss Federal Institute of Technology (ETH), Zurich. The presumed audience is graduate mechanical or electrical engineering students. The prerequisites are general engineering topics and a first course in optimal control theory. Readers with little preparation in that area are referred to [30]. The most important results of parameter optimization and optimal control theory are summarized in Appendix II.

Why has this text been written?

Individual mobility relies to a large extent on passenger cars. These vehicles are responsible for a large part of the world's consumption of primary energy carriers, mostly fossil liquid hydrocarbons. The specific application profiles of these vehicles, combined with the inexorably increasing demand for mobility, have led to a situation where the reduction of fuel consumption has become a top priority for the society and the economy.

Many approaches that permit to reduce the fuel consumption of passenger cars have been presented so far and new ideas emerge on a regular basis. In most – if not all – cases these new systems are more complex than the traditional approaches. Additional electric motors, storage devices, torque converters, etc. are added with the intention to improve the system behavior. For such complex systems the traditional heuristic design approaches fail.

The only way to deal with such a high complexity is to employ mathematical models of the relevant processes and to use these models in a systematic (“model-based”) way. This text focuses on such approaches and provides an

introduction to the modeling and optimization problems typically encountered by designers of new propulsion systems for passenger cars.

What can be learned from this text?

This book analyzes the longitudinal behavior of road vehicles only. Its main emphasis is on the analysis and minimization of the energy consumption. Other aspects that are discussed are drivability and performance.

The starting point for all subsequent steps is the derivation of simple yet realistic mathematical models that describe the behavior of vehicles, prime movers, energy converters, and energy storage systems. Typically, these models are used in a subsequent optimization step to synthesize optimal vehicle configurations and energy management strategies.

Examples of modeling and optimization problems are included in Appendix I. These *case studies* are intended to familiarize the reader with the methods and tools used in powertrain optimization projects.

What cannot be learned from this text?

This text does not consider the pollutant emissions of the various powertrain systems because the relevant mechanisms of the pollutant formation are described on much shorter time scales than those of the fuel consumption. Moreover, the pollutant emissions of some prime movers are virtually zero or can be brought to that level with the help of appropriate exhaust gas purification systems. Readers interested in these aspects can find more information in [100].

Comfort issues (noise, harshness, and vibrations) are neglected as well. Only those aspects of the lateral and horizontal vehicle dynamics that influence the energy consumption are briefly mentioned. All other aspects of the horizontal and lateral vehicle dynamics, such as vehicle stability, roll-over dynamics, etc. are not discussed.

Acknowledgments

Many people have implicitly helped us to prepare this manuscript. Specifically our teachers, colleagues, and students have contributed to bring us to the point where we felt ready to write this text. Several people have helped us more explicitly in preparing this manuscript: Hansueli Hörler, who taught us the basic laws of engine thermodynamics, Alois Amstutz and Chris Onder who contributed to the development of the lecture series behind this text, those of our doctoral students whose dissertations have been used as the nucleus of several sections (we reference their work at the appropriate places), and Brigitte Rohrbach, who translated our manuscripts from “Italish” to English.

June 2005

Lino Guzzella and Antonio Sciarretta

Preface

Why a second edition?

The discussions about fuel economy of passenger cars have become even more intense since the first edition of this book appeared. Concerns about the limited resources of fossil fuels and the detrimental effects of greenhouse gases have spurred the interest of many people in industry and academia to work towards reduced fuel consumption of automobiles. Not surprisingly, the first edition of this monograph sold out rather rapidly. When the publisher asked us about a second edition, we decided to use this opportunity to revise the text, to correct several errors, and to add new material.

The following list includes the most important changes and additions we made:

- The section describing battery models has been expanded.
- A new section on power split devices has been added.
- A new section on pneumatic hybrid systems has been added.
- The chapter introducing supervisory control algorithm has been rewritten and expanded.
- Two new case studies have been added.
- A new appendix that introduces the main ideas of dynamic programming has been added.

Acknowledgements

We want to express our gratitude to the many colleagues and students who reported to us errors and omissions in the first edition of this text. Several people have helped us improving this monograph, in particular Christopher Onder who actively participated in the revisions.

June 2007

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Introduction

This introductory chapter shows how the problems discussed in this text are embedded in a broader setting. First a motivation for and the objective of the subsequent analysis is introduced. After that the complete energy conversion chain is described, starting from the available primary energy sources and ending with the distance driven. Using average energy conversion efficiency values, some of the available options are compared. This analysis shows the importance of the “upstream” processes. The importance of the selected on-board energy carrier (“fuel”) is stressed as well. In particular its energy density and the safety issues connected with the refueling process are emphasized. The last section of this first chapter lists the main options available for reducing the energy consumption of passenger vehicles.

1.1 Motivation

The main motivation to write this book is the inexorably increasing number of passenger cars worldwide. As Fig. 1.1 shows, some 800 million passenger cars are operated today. More interesting than this figure is the trend that is illustrated in this figure for the example of the United States of America (the same trend is observed in Japan and Europe): in wealthy societies the car density saturates at a ratio of approximately 400 to 800 cars per 1000 inhabitants.

It is corroborated empirically that the demand for personal transportation increases with the economic possibilities of a society [220]. Therefore, if the car density mentioned above is taken as the likely future value for other regions of the world, serious problems are to be expected. Countries such as China (1.3 billion inhabitants) or India (1.1 billion inhabitants) in the year 2007 have car densities of around 30 cars per 1000 inhabitants. Accordingly, in the next 20 years the car density in these countries will increase substantially, which will further increase the pressure on fuel prices and cause serious problems to the environment.

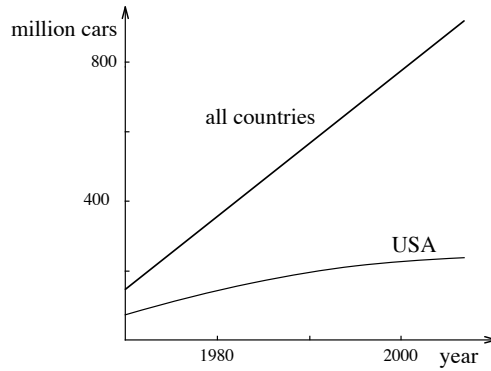


Fig. 1.1. *Schematic* representation of the development of the number of passenger cars operated worldwide.

In the face of these trends, it is clear that new fuel sources must be developed and that the fuel consumption of passenger cars must be reduced substantially. This text focuses on the second approach.

1.2 Objectives

The main objectives of this text are to introduce mathematical models and optimization methods that permit a systematic minimization of the *energy consumption* of vehicle propulsion systems. The objects of this analysis are *passenger cars*, i.e., vehicles that

- are autonomous and do not depend on fixed energy-providing grids;
- have a refueling time that is negligible compared to the driving time between two refueling events;
- can transport two to six persons and some payload; and
- accelerate in approximately 10 to 15 seconds from 0 to 100 km/h, or can drive uphill a 5% ramp at the legal top speed, respectively.¹

These requirements, which over the last one hundred years have evolved to a quasi-standard profile, substantially reduce the available options. Particularly the first and the second requirement can only be satisfied by few *on-board* energy storage systems, and the performance requirements can only be satisfied by propulsion systems able to produce a maximum power that is substantially larger than the power needed for most driving conditions.

A key element in all considerations is the on-board energy carrier system. This element must:

¹ These numerical values are only indicative. It goes without saying that the performance range is very wide.

- provide the highest possible energy density²;
- allow for the shortest possible refueling time; and
- be safe and cause no environmental hazards in production, operation, and recycling.

The number of components that are necessary to realize modern and in particular future propulsion systems is inexorably increasing. Improved performance and fuel economy can only be obtained with complex devices. Of course, these subsystems influence each other. The best possible results are thus not obtained by an isolated optimization of each single component. Optimizing the entire system, however, is not possible with heuristic methods due to the “curse of exponential growth.” The only viable approach to cope with this dilemma is to develop mathematical models of the components and to use model-based numerical methods to optimize the system structure and the necessary control algorithms. These models must be able to *extrapolate* the system behavior. In fact, such an optimization usually takes place before the actual components are available or requires the devices to operate in unexpected conditions. For these reasons, only first-principle models, i.e., models that are based on physical laws, will be used in this text.

Of course, some of the mathematical models and methods introduced in this text may be useful for the design of other classes of vehicles (trains, heavy-duty trucks, etc.). However, there are clear differences³ that render the passenger car optimization problem particularly interesting.

At least three energy conversion steps are relevant for a comprehensive analysis of the energy consumption of passenger cars. As illustrated in Fig. 1.2, the actual energy source is one of the available primary energy carriers (chemical energy in fossil hydrocarbons, solar radiation used to produce bio mass or electric energy, nuclear energy, etc.). In a first step, this energy is converted to an energy carrier that is suitable for on-board storage, i.e., to a “fuel” (examples are gasoline, hydrogen, etc.). This “fuel” is then converted by the propulsion system to mechanical energy that, in part, may be stored as kinetic or potential energy in the vehicle. The third energy transformation is determined by the vehicle parameters and the driving profile. In this step, the mechanical energy produced in the second conversion step is ultimately dissipated to thermal energy that is deposited to the ambient. The terms “well-to-tank,” “tank-to-vehicle,” and “vehicle-to-miles” are used in this text to refer to these three conversion steps. Unfortunately, all of these conversion processes cause substantial energy losses.

² The energy density here is defined as the amount of *net* energy available for propulsion purposes divided by the mass of the energy carrier necessary to generate that propulsion energy, including all containment elements but not the on-board energy transformation devices.

³ For instance, the autonomy requirement and the dominance of part-load operation will be relevant for the optimization problems.

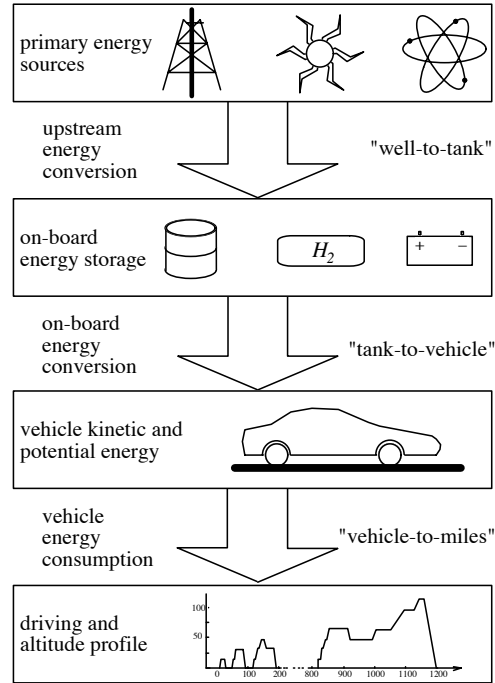


Fig. 1.2. The main elements of the energy conversion scheme.

This text will not address any control problems pertaining to the “well-to-tank” energy conversion. The systems used for that conversion are very large power plants, refineries, or other process engineering systems. Of course, their average efficiency values and pollutant emission have an important impact on the economy and ecology. However, the problems arising in that area and the methods required to solve those problems belong to a different class.

In the next section an overview of the most important energy conversion approaches is presented. With this information, a preliminary estimation of the total energy consumption is possible. Note that a correct comparison is not easy, if at all possible.⁴ Readers interested in a broader discussion are referred to [34].

The main physical phenomena influencing the “vehicle-to-miles” energy conversion will be discussed in Chap. 2. That chapter will mainly introduce descriptions that are *quasistatic* (this term will be precisely defined below),

⁴ For instance, the total “well-to-miles” carbon dioxide emissions are often used to compare two competing approaches. However, such a discussion is not complete unless the “gray” energy invested in the vehicles, refineries and plants is considered. Even more difficult: how to take into account the problems associated with nuclear waste repositories, landscape degradation caused by windmills, or nitric oxide emission of coal-fired power plants?

but also *dynamic* models will be presented. In this context, it is important to understand the impact of the driving profile that the vehicle is assumed to follow. As mentioned above, only those effects are considered that have a substantial influence on the energy consumption.

The main emphasis of this text is on the modeling and optimization of the “tank-to-vehicle” energy conversion systems. For this problem suitable mathematical models of the most important devices will be introduced in Chaps. 3 through 6. Chapter 7 presents methods with which the energy consumption can be minimized. All of these methods are model-based, i.e., they rely on the mathematical models derived in the previous chapters and on systematic optimization procedures to find (local) minima of precisely cast optimization problems. Eight case studies are included in Appendix I. Appendix II then summarizes the most important facts of parameter optimization and optimal control theory and Appendix III introduces the main ideas of dynamic programming.

1.3 Upstream Processes

As mentioned above, a detailed analysis of the “well-to-tank” energy conversion processes is not in the scope of this text. However, the efficiency and the economy of these systems are important aspects of a comprehensive analysis. For this reason a rather preliminary but nevertheless instructive overview of the main energy conversion systems is given in this section.

Figure 1.3 shows a part of that complex network. The efficiency numbers given in that figure are approximate and are valid for available technology. The CO₂ factors relate the amount of carbon dioxide emitted by using one energy unit of natural gas or coal to the amount emitted when using one energy unit of oil.⁵ Solar and nuclear primary energy sources are assumed to emit no CO₂, i.e., the gray energy and the associated CO₂ emission are not shown in that figure.

Only three systems are considered in Fig. 1.3 for the conversion of “fuel” to mechanical energy: a spark-ignited (SI) or gasoline internal combustion engine (ICE), a compression-ignited (CI) or Diesel ICE, and an electric motor. Average “tank-to-vehicle” efficiencies of these prime movers are shown in Fig. 1.3 as well.⁶ The mechanical energy consumption (the “vehicle-to-miles” efficiency) is approximated by an equation that is valid for the European test cycle (this expression will be introduced in Sect. 2.2). With the information shown in Fig. 1.3 it is easy to make some preliminary, back-of-the-envelope-style calculations that, despite the many uncertainties, are quite instructive.

⁵ The CO₂ factors reflect the different chemical composition *and* the different heating values. The base line is defined in Table 1.1.

⁶ The peak efficiencies of all of these devices are (substantially) higher. However, the relevant data are the cycle-averaged efficiencies, which are close to the values shown in Fig. 1.3.

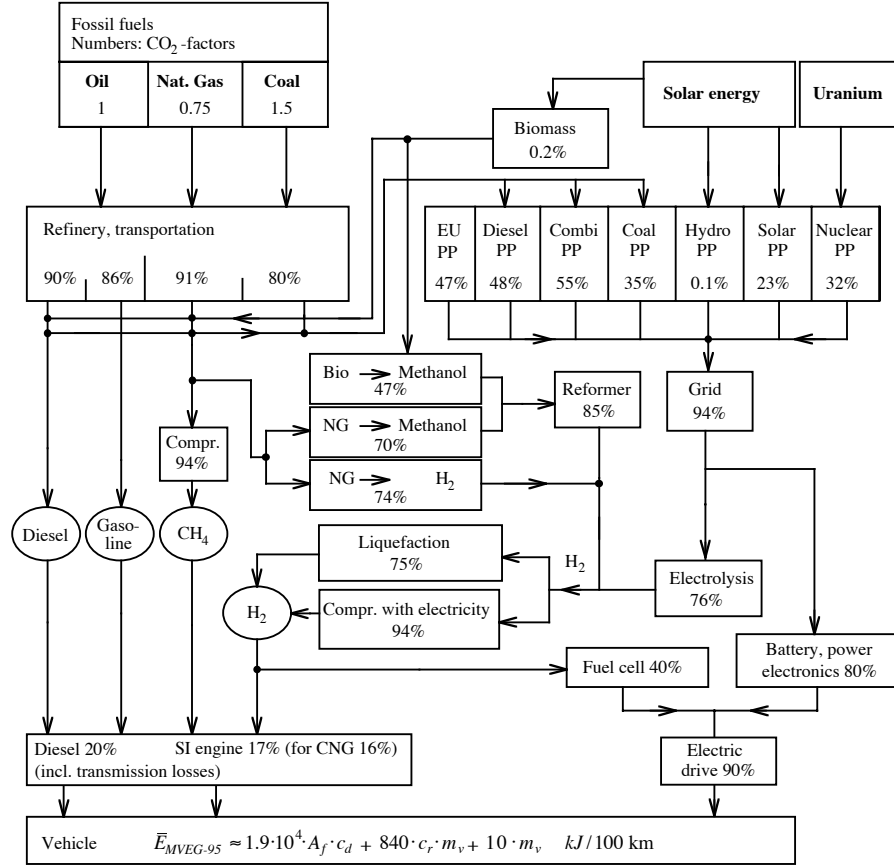


Fig. 1.3. Different paths to convert a primary energy source to mechanical energy needed to drive a car in the MVEG-95 test cycle. Source: [69] and own data.

For that purpose Table 1.1 summarizes some of the most important parameters of the fuels considered below.

Table 1.1. Main parameters of some important energy carriers (lower heating value H_l , hydrogen-to-carbon ratio H/C , and mass of CO_2 emitted per mass fuel burned ν); CNG = compressed natural gas.

	H_l (MJ/kg)	H/C	ν
oil	43	≈ 2	3.2
CNG (\approx methane)	50	4	2.75
coal (\approx carbon)	34	0	3.7
hydrogen	121	∞	0

Figure 1.4 shows the “well-to-miles” carbon dioxide emissions of three ICE-based powertrains. The vehicle assumed in these considerations is a standard mid-size passenger car. The efficiency values of the gasoline and Diesel engines are standard values as well. The efficiency of CNG engines is usually slightly smaller than the one of gasoline SI engines [12].

Of course this analysis neglects several important factors, for instance the greenhouse potential of methane losses in the fueling infrastructure. Nevertheless, the results obtained indicate that increasing the numbers of CNG engines could be one option to reduce CO₂ emissions with relatively small changes in the design of the propulsion system. Unfortunately, as mentioned before, the “well-to-miles” CO₂ emission levels are just one element of the problem space. In this case, the reduced energy density of CNG as on-board energy carrier has, so far, inhibited a broader market penetration of this vehicle class. The next section will show more details on this aspect.

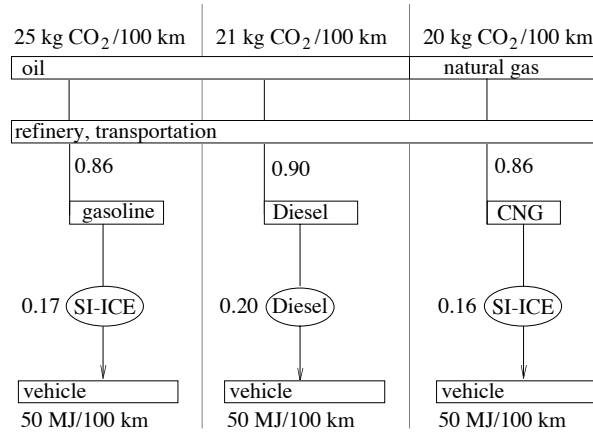


Fig. 1.4. “Well-to-miles” CO₂ emission of three conventional powertrains. The vehicle is described by the parameters $m = 1600$ kg, $c_d \cdot A_f = 0.86$ m², and $c_r = 0.013$ (see Chap. 2). The fuel properties are defined in Table 1.1.

Figure 1.5 shows what amount of CO₂ emissions can be expected when a battery-electric propulsion system is employed. The base vehicle is assumed to have the same⁷ parameters as the one used to compute the values shown in Fig. 1.4. Several primary energy sources are compared in this analysis. The two CO₂-neutral⁸ energy sources (solar and nuclear energy) produce no

⁷ Of course the batteries substantially increase the vehicle mass. Here the (optimistic) assumption is adopted that the recuperation capabilities of the battery electric system compensate for the losses that are caused by this additional mass.

⁸ As mentioned, only the CO₂ emission caused by the operation of the power plants are considered.

carbon dioxide emission. However, if the electric energy required to charge the batteries is generated using fossil primary energy sources, surprisingly different CO₂ emission levels result.

In the case of a natural-gas-fired combined-cycle power plant (PP) the CO₂ emission levels are substantially lower than those of traditional ICE-based propulsion systems. However, if the other limit case (coal-fired steam turbines) is taken into consideration, the “well-to-miles” carbon dioxide emission levels of a battery-electric car become even worse than those of the worst ICE-based propulsion system.⁹ Moreover, in the next section it will be shown that the energy density of batteries is so small that battery electric vehicles cannot satisfy the specifications of a passenger car as defined in Sect. 1.2.

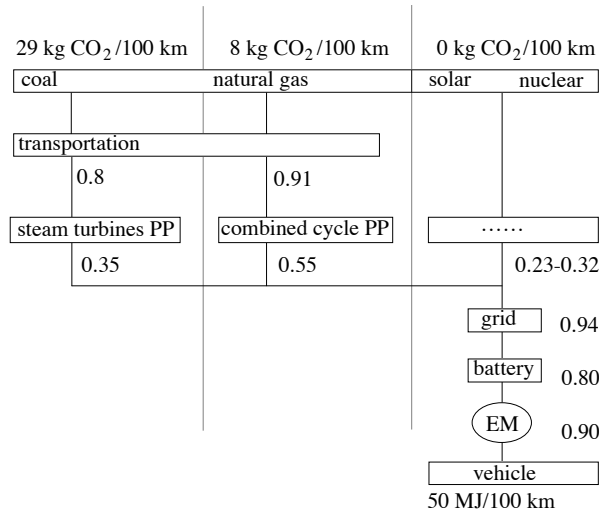


Fig. 1.5. “Well-to-miles” CO₂ emission of a battery electric vehicle. Vehicle parameters as in Fig. 1.4. Battery efficiency includes charging, discharging, and power electronic losses. The fuel properties are defined in Table 1.1.

As a last example, the estimated “well-to-miles” CO₂ emission levels of a fuel cell electric vehicle are shown in Fig. 1.6. Again, the vehicle parameters have been chosen to be the same as in the conventional case. The efficiency of the fuel cell *system* has been assumed to be around 0.40. Despite many more optimistic claims, experimental evidence, as the one published in

⁹ Of course, low CO₂ primary energy sources should first be used to replace the worst polluting power plants that are part of the corresponding grid. In this sense, each unit of *additional* electric energy used must be considered to have been produced by the power plant in the grid that has the *worst* efficiency. Accordingly, in the example shown in Fig. 1.5 the relevant CO₂ emission number is the one valid for coal-fired power plants.

[212], has shown that the net efficiency of a fuel cell *system* will probably be close to that figure.¹⁰ Even more uncertain are the efficiencies of on-board gasoline-to-hydrogen reformers. Including all auxiliary devices, a net efficiency of approximately 60–70% may be expected.

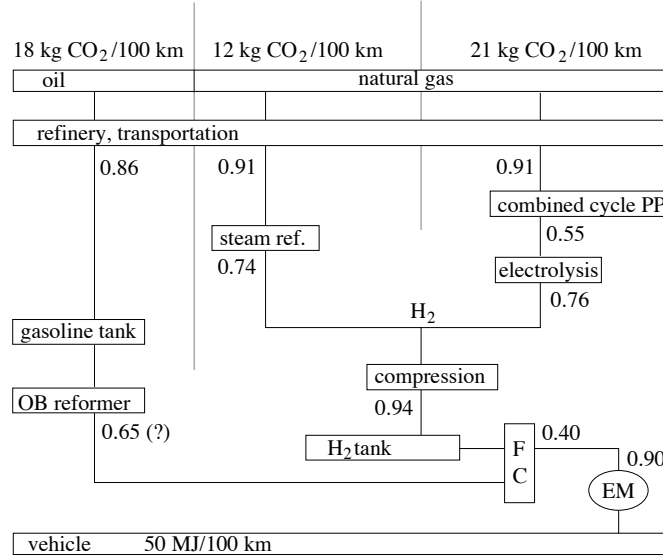


Fig. 1.6. “Well-to-miles” CO₂ emission of a fuel cell electric vehicle. Vehicle parameters as in Fig. 1.4. The efficiency of the on-board gasoline-to-hydrogen reformer is not experimentally verified. The fuel properties are defined in Table 1.1.

The main insight that can be gained from Fig. 1.6 is that as long as fossil primary energy sources are used fuel cell electric vehicles have a potential to reduce the “well-to-miles” CO₂ emission only if the hydrogen is produced in a steam reforming process using natural gas as primary energy source. As shown in Fig. 1.6, fuel-cell-based powertrains have excellent “tank-to-vehicle” but rather poor “well-to-tank” efficiencies. This fact will become very important once *renewable* primary energy sources are available on a large scale. If this comes true, then the “upstream” CO₂ emission levels are zero and the only concern will be to utilize the available on-board energy as efficiently as possible. In this situation fuel-cell-based propulsion systems might prove to be the best choice.

¹⁰ Fuel cells must be supercharged to achieve sufficient power densities and to exploit in the best possible way the expensive electrochemical converters. The compressors that are necessary for that consume in the order of 20–25 percent of the electric power produced by the fuel cell [212].

1.4 Energy Density of On-Board Energy Carriers

As mentioned above, the energy density of the on-board energy carrier is one of the most important factors that influence all choices of propulsion systems for individual mobility purposes. Figure 1.7 shows *estimations* of the corresponding figures for some commonly used or often proposed “fuels.” All values are approximate and include the average losses caused by the corresponding “tank-to-vehicle” energy conversion system as shown in Figure 1.3.

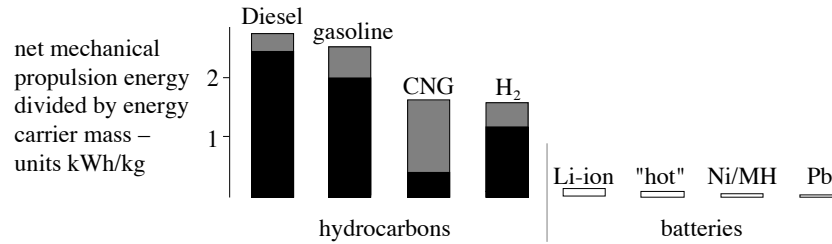


Fig. 1.7. Estimates of the *net* energy density of several on-board energy carriers.

For Diesel and gasoline the lower values (black bars) are obtained using actual average engine efficiencies, the upper values (gray bars) are valid for existing, but not yet standard engine systems (hybrid-electric propulsion, downsized-supercharged gasoline engine systems, etc.).

Compressed natural gas (CNG) is stored in gaseous form. Standard engine systems have 16% efficiency and the corresponding storage systems¹¹ are rated at 200 bar yielding the energy density indicated in Fig. 1.7 by a black bar. Advanced engine systems can reach more than 20% efficiency and advanced storage systems can go up to 350 bar,¹² yielding the energy density indicated by the gray bar.

Hydrogen may be stored under high pressure (black bar valid for 350 bar and carbon fibre bottles) or liquefied (gray bar).¹³ The energy densities shown in Figure 1.7 are based on an cycle-averaged conversion efficiency of fuel cells of 40%. The main reason for the relatively low energy density of gaseous hydrogen is the unfavorable ratio of heating value divided by gas constant.

¹¹ Conventional steel bottles have a mass to volume ratio of approximately 1 kg/l; bottles made of carbon fibres have substantially lower mass to volume ratios of approximately 0.3-0.4 kg/l.

¹² For CNG higher pressures are not foreseeable: the compression losses become too large and outweigh the gains in energy density.

¹³ Of course this approach induces an additional substantial penalty of approximately 30% in the “well-to-tank” efficiency and causes problems for long-term on-board storage since no insulation is perfect. The heat transfer to the liquid fuel will therefore either lead to some fuel evaporation and a subsequent venting or require a constant energy supply to avoid such evaporation losses.

The electrochemical on-board energy carriers have the lowest energy density of those “fuels” shown in Fig. 1.7, despite the fact that the electric “tank-to-vehicle” conversion systems have a very high conversion efficiency. State-of-the-art batteries optimized for high energy density achieve approximately 40 Wh/kg for lead–acid, 70 Wh/kg for nickel–metal hydrides, 150 Wh/kg for “hot” batteries such as the sodium–nickel chloride “zebra” battery, and 180 Wh/kg for lithium-ion cells.¹⁴ Taking the average “tank-to-vehicle” conversion efficiency to be around 80%,¹⁵ the values illustrated in Fig. 1.7 result. Not surprisingly, none of the several battery-electric vehicle prototypes that have been developed in the past has ever evolved to become a mass-produced alternative to the existing solutions.

Batteries are, however, very interesting “medium-term” energy storage devices, which can help to improve the efficiency of other propulsion systems. Such *hybrid* powertrains will be analyzed in detail in Chap. 4 and in several case studies in Appendix I.

Note that there are several other ways to store energy on-board, notably supercapacitors (electrostatic energy), hydraulic and pneumatic reservoirs (potential energy), and flywheels (kinetic energy). All of these systems have similar or even smaller net energy densities than lead acid batteries.¹⁶ However, supercapacitors and similar devices have relatively high *power* densities, i.e., they may be charged and discharged with high power.¹⁷ Such “short-term” energy storage devices can be useful for the recuperation of the kinetic energy stored in the vehicle that would otherwise be lost in braking maneuvers. More details on these aspects can be found in Chaps. 2 and 4.

The main point illustrated in Figure 1.7 is that with respect to energy density, liquid hydrocarbons are unquestionably the best fuels for passenger car applications. These fuels have several other advantages:

- the refueling process is fast (several MW of power), safe, and does not require any expensive equipment;
- their long-term storage is possible at relatively low costs; and
- there were and still are large and easily exploitable reserves of crude oil.¹⁸

¹⁴ Unfortunately, lithium-ion cells are not yet available for automotive mass production.

¹⁵ This figure includes the losses in the transmission, in the electric motor, in the power electronics and in the battery discharging process.

¹⁶ Supercapacitors can reach net energy densities in the order of 5 Wh/kg. Systems based on pneumatic air stored at 300 bars in bottles made of carbon fibre can reach net energy densities in the order of 20 Wh/kg.

¹⁷ Batteries can also be optimized for high power density. However, in this case their energy densities are lower than those figures indicated in Fig. 1.7.

¹⁸ Note that liquid hydrocarbons need not originate from crude oil sources. Many approaches that use fossil (natural gas, coal, etc.) and renewable (bio Diesel, ethanol, etc.) primary energy sources are known with which liquid hydrocarbons can be synthesized.

Particularly the last point is, of course, the topic of many vivid debates. This text does not attempt to contribute to these discussions. However, following the paradigm of a “least-regret policy,” the standing assumption adopted here is that the improvement of the “tank-to-miles” efficiency, while satisfying the performance and cost requirements, is worth the efforts.

1.5 Pathways to Better Fuel Economy

As illustrated in Fig. 1.2, there are essentially three possible approaches to reducing the total energy consumption of passenger cars:

- Improve the “well-to-tank” efficiency by optimizing the upstream processes and by utilizing alternative primary energy sources.
- Improve the “tank-to-vehicle” efficiency, as discussed below.
- Improve the “vehicle-to-miles” efficiency by reducing the vehicle mass and its aerodynamic and rolling friction losses.

As mentioned above, the optimization of the “well-to-tank” efficiency is an important area in itself. These problems are not addressed in this text. The phenomena which define the “vehicle-to-miles” energy losses will be analyzed in this text, but no attempt is made to suggest concrete approaches to reduce these losses. In fact, the disciplines that are important for that are material science, aerodynamics, etc. which are not in the scope of this monograph.

This text focuses on improving the “tank-to-vehicle” efficiency. Three different approaches are discernible on the component level and two on the system level:

1. Improve the *peak* efficiency of the powertrain components.
2. Improve the *part-load* efficiency of the powertrain components.
3. Add the capability to *recuperate* the kinetic and potential energy stored in the vehicle.
4. Optimize the structure and the parameters of the propulsion system, assuming that the fuel(s) used and the vehicle parameters are fixed.
5. Realize appropriate supervisory control algorithms that take advantage of the opportunities offered by the chosen propulsion system configuration.

Items 2–5 will be discussed in detail in this text, while item 1 is not within its scope. On one hand that optimization requires completely different methods and tools and, on the other hand, the potential for improvements in that area, in most cases, is rather limited. Compared to the peak efficiency of Diesel (≈ 0.40) or gasoline (≈ 0.37) engines, the part-load efficiency, which determines the actual fuel consumption in regular driving conditions, is much smaller (on average ≈ 0.20 for Diesel and ≈ 0.17 for gasoline engines). Therefore, the potential offered by improving these figures is much larger. Optimized powertrain systems and appropriate control algorithms are instrumental to achieve that objective.