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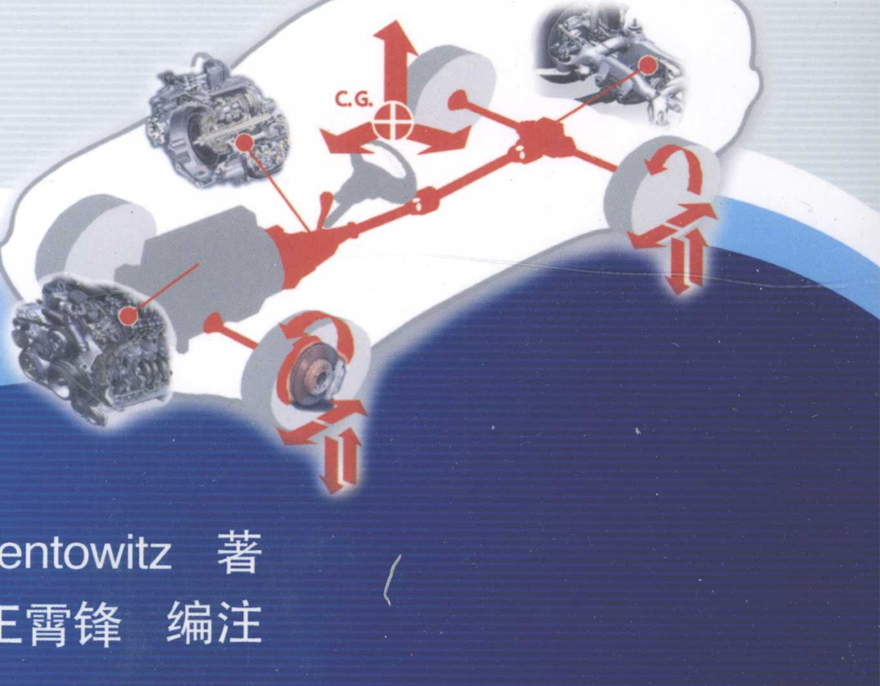
汽车工程学Ⅰ：
汽车纵向动力学（英文版）

Automotive Engineering Ⅰ:
Longitudinal Dynamics of Vehicles



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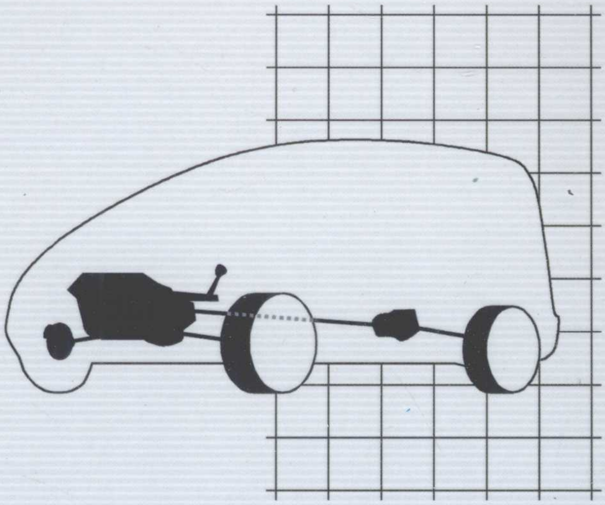
Longitudinal Dynamics of Vehicles

- Traffic system motor vehicle
- Power and energy demand
- Drivetrain
- Vehicle dynamics



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汽车工程学Ⅰ：汽车纵向动力学

Automotive Engineering Ⅰ: Longitudinal Dynamics of Vehicles

（英文版）

（德）亨宁·瓦伦托维兹（Henning Wallentowitz） 著
王霄锋 编注

机 械 工 业 出 版 社

本书主要介绍汽车的行驶性能和制动性能，即汽车的直线行驶性能。本书内容主要包括：交通系统与汽车，汽车经济方面的问题，车轮阻力，空气动力阻力，爬坡阻力，加速阻力，汽车发动机，电驱动，混合动力，离合器，变速器，差速器，制动器，制动传动系统，传动系振动，车辆的驱动性能，车辆的燃油消耗，传动系布置，驱动极限，摩擦限制的制动能力，制动力分配，制动力控制和制动力调节。

该书内容比较新，较为全面地介绍了与汽车直线行驶性能相关的结构、技术和理论，视角比较独特，除用于高等学校车辆工程专业的双语教学外，还可以作为汽车工程师的参考书。

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Preface

This book is used for lecturing the basics of automotive engineering at RWTH Aachen University. The automotive lectures in total are organized according to the different degree of freedom of the vehicle movement. Thus this book is one out of the row and it is covering the longitudinal dynamics of vehicles.

General remarks in the introduction are covering the motor vehicle as a traffic system and the economic aspects of the motorised traffic. In the technical part of this book we are starting with the driving resistances of the car, like rolling resistance, aerodynamic resistance and the acceleration resistance. Thus, the energy demand of the car is defined. With respect to the delivered power we are following the force flow in the car. Different energy sources and different engines (motors) are considered. Speed- and torque-converters are transferring the energy flow via the differentials to the wheels. The co-operation between the demanded power by the vehicle and the delivered power by the engines is discussed. Rules for gearbox design are found.

The brakes are covered in the following chapter. Starting from fundamental requirements, different systems and special design features are described. Disc-and drum brakes for passenger cars and for commercial vehicles are discussed. Even the last development step, covering electric brakes, is mentioned.

The last chapter deals with vehicle dynamics for longitudinal driving (lateral and vertical dynamics is dealt with in another book). Driving performance with respect to the available power and the fuel consumption is evaluated. Then different drive-train layouts and afterwards the performances of these drive-trains with respect to road friction are discussed. The theoretical, but very practical related discussion is closed with brake force distribution.

As a summary this book contains a lot of basic automotive knowledge. But this knowledge is really usable for engineers in practice. With this knowledge in mind a lot of other problems can be solved.

H. Wallentowitz

Univ.-Prof. Dr.-Ing. Henning Wallentowitz

前　言

Foreword

竞争的全球化带来了教育的国际化。教育国际化使得高等学校有机会了解、引进和使用国外的优秀教育资源，有利于拓展学生的国际视野，加强与国际同行的交流。亚琛工业大学（RWTH Aachen University）是德国知名的工科大学之一，在汽车工程领域享有很高的国际声誉。2001年中德双方教育部门共同推出了“清华—亚琛联合硕士生培养项目”，双方共同制订联合培养方案，确定以英语作为教学语言，双方教师共同授课。双方每年互派学生、交换教师，进行教学交流和科研合作。通过开展合作研究以及对研究生的联合培养，借鉴国际先进的教育理念和做法，引进优秀的教育资源，提高了研究生培养质量、教师的教学水平和学术水平，同时提升了学科水平和清华在国际上的影响力。清华学生得益于德国世界先进的工程教育，加强了工程实践能力，在国际环境中的学习研究经历也有利于学生了解异国文化。清华—亚琛联合研究生培养项目是对我国教育部“强强联合”倡导的具体实施。该项目在清华联合培养方面为双方延伸出一个广阔的合作平台，是建设“综合性、研究型、开放式”的世界一流大学中的重要举措。截止2008年6月，清华大学汽车工程系已选派54名研究生和12名教师赴亚琛工大学习和交流，其中28名研究生已获得亚琛工大硕士学位；同期内，亚琛工大汽车研究所向清华选派了39名研究生，其中30名已返回亚琛。2007年11月，清华大学顾秉林校长赴亚琛向8名亚琛工大的学生授予清华大学硕士学位。

本书编者Henning Wallentowitz教授是“清华—亚琛联合硕士生培养项目”发起者，具有丰富的工程实践背景、很深的学术造诣和教学经验。Wallentowitz教授1978～1985年在Daimler Benz（戴母勒奔驰）汽车公司但任实验室工程师开发部负责人，1985～1992年在BMW（宝马）汽车公司悬架开发部担任主任工程师，1992～1993年担任BMW（宝马）技术股份有限公司董事长，1997～2004年担任亚琛工业大学副校长，2004年被聘为清华大学兼职教授。他在亚琛工业大学主要承担了Automotive Engineering（汽车工程），Structural design of motor vehicles（汽车结构设计），Mechatronics in Vehicle Engineering（车辆机电一体化系统），Motorbikes（摩托车），Plastics in Automotive Application（汽车中的塑料应用），Interior and Exterior Vehicle Noise（汽车内外噪声）等课程的教学。

本书不同于传统的“汽车理论”和“汽车设计”，反映了德国汽车工程的教学内容和教学模式以及汽车先进技术，具有全新的教材体系，共分三部分。

《汽车工程学Ⅰ》比较全面地介绍汽车的行驶性能和制动性能，即汽车的直线行驶性能。内容主要包括：交通系统与汽车；汽车的经济方面；车轮阻力；空气动力阻力；爬坡阻力；加速阻力；汽车发动机；电驱动；混合动力；离合器；变速器；差速器；制动器；制动传动系统；传动系振动；车辆的驱动性能；车辆的燃油消耗；传动系布置；

驱动极限；摩擦限制的制动能力；制动力分配；制动力控制；制动力调节。该书内容比较新，覆盖面宽，视角独特，对汽车专业的本科生、研究生以及汽车工业的工程师都具有比较大的参考价值。

《汽车工程学Ⅱ》介绍了汽车侧向动力学和垂向动力学的相关基础理论和典型的应用系统。以动力学为基础，分析了轮胎、转向系、悬架等结构的建模、动力学方程及结构参数与系统动力学特性的相互关系，并提出了相关系统参数的设计准则。其内容丰富，理论与实际结构参数的设计方法紧密联系，具有较高的工程应用价值。

《汽车工程学Ⅲ》比较全面地介绍了与汽车安全相关的理论和各模块系统。在汽车横向、纵向动力学控制理论的基础上，介绍了碰撞事故分析和碰撞前后分析的方法，详细阐述了传动总成、照明系统、空调系统、汽车玻璃、驾驶员视线控制、驾驶辅助系统等车内模块的安全特性，并基于生物力学论述了乘员约束系统和行人碰撞安全。内容新颖，在系统介绍汽车安全理论的同时，还涵盖了与汽车安全相关的最新技术成果，并预测了汽车安全技术发展的方向。

清华大学汽车工程系车辆工程专业相关教师在 Wallentowitz 教授编写的汽车工程讲义的基础上，对该系列汽车工程双语教材进行了编注，在每一章结尾着重对其中的专业词句和疑难字句进行了中文注释。其中王霄锋副教授负责编注《汽车工程学Ⅰ》，李克强教授负责编注《汽车工程学Ⅱ》，周青教授和桂良进副研究员带领研究生对《汽车工程学Ⅲ》进行了编注。

本书三部分内容具有很强的工业背景，对于我国借鉴德国的教材编写方式和教学模式具有比较大的参考价值。本书除作为高校汽车专业教学用书外，还可以作为汽车工程师的参考书。

清华大学
汽车工程系

目　　录

Contents

1 Introduction

The volume on hand deals with longitudinal dynamics of motor vehicles. This generic term summarizes the processes and systems that influence the motor vehicle's movement in the longitudinal direction [1-1]. Before dealing with the particular processes and systems, the importance of motor vehicles in our society as well as some of the resulting problems need to be pointed out.

1.1 Traffic system motor vehicle

Generally speaking, the conditions and development objectives for road traffic can be outlined by considering it as a "black-box" according to Fig. 1-1 and by comparing the expenses with the results.

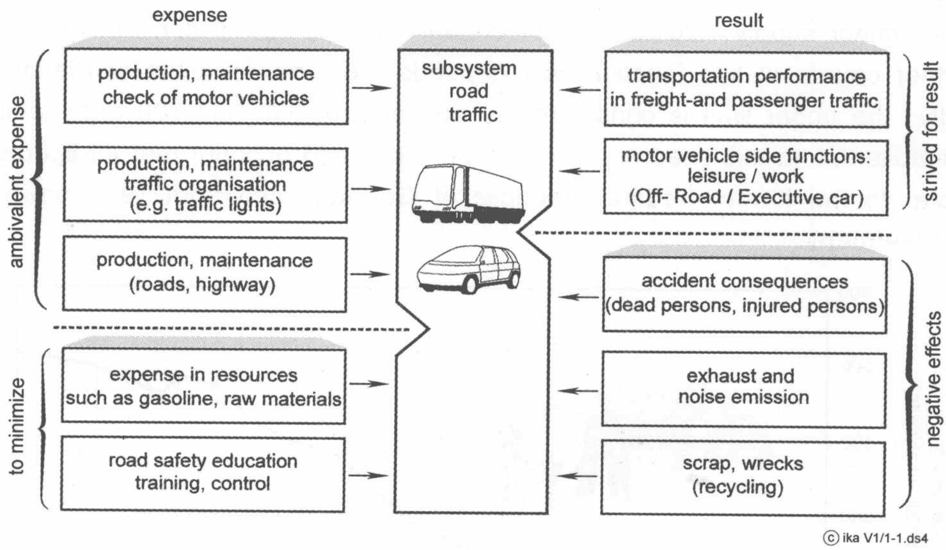

Fig. 1-1 Expenses and results of the system "road traffic"

Considering this simplified approach, the result strived for is the achieved transportation performance, on the one hand with minor negative side effects and on the other hand with minor expenses-e. g. limited resources such as crude oil. The expenses, for e. g. the production of motor vehicles, have so far been described as ambivalent since they are linked with value addition and the work place. This, however, implies that costs emerging due of this have to be minimized.

An economical cost-benefit analysis of these complex interrelations does not exist so far as all expenses and result factors can't be monetarily quantified. In future, the reduction of road traffic's negative effects would however gain considerable importance. This importance would be due to people's growing consciousness in ecology and the modern technological possibilities.

1.1.1 Means of transportation

Generally speaking, the motor vehicle can be defined as a non-rail-bound land vehicle which serves to cover distance. Considering the means of transportation, we distinguish between passenger-and freight traffic.

1.1.1.1 Passenger traffic

The development of passenger traffic in the Federal Republic of Germany is marked by an increasing degree of motorisation. This motorisation can be described either by the absolute number of motor vehicles or by vehicle density. The total amount of motor vehicles registered in the Federal Republic by the end of 1996 was about 48.1 millions; this included approx. 41 million automobiles.

Fig. 1-2 shows the growth of vehicle density in the Federal Republic of Germany. A typical growth function can be noticed in the past, which after a stage of disproportional increase (minor supply, high demand) changed to a stage of constant growth rate. The further course of this function was dependent on the so-called saturation point. Presently, the upper limit is considered to be between 650 and 700 automobiles per 1000 inhabitants. In this chapter, it has to be taken into account that all figures up to 1990 refer to the former Federal Republic of Germany and from 1991 onwards for reunited Germany.

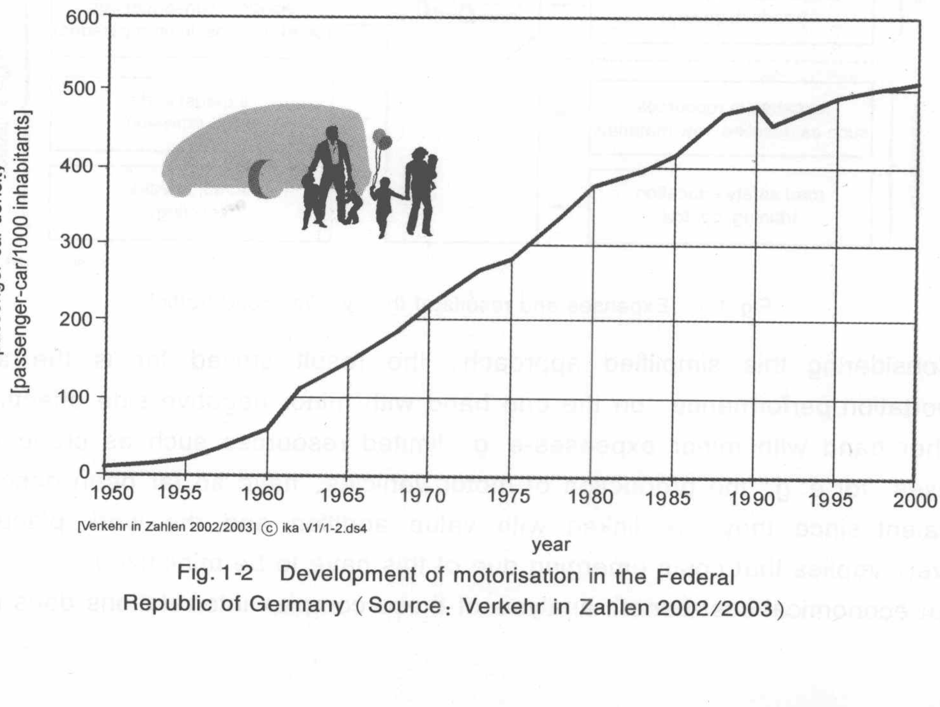

Fig. 1-2 Development of motorisation in the Federal Republic of Germany (Source: Verkehr in Zahlen 2002/2003)

The increase of automobile density (meaning the degree of motorisation) runs parallel to the decrease of automobile's mileage. It decreased from an average of 14600km/a (9072miles/a) in 1975 to 12700km/a (7892miles/a) in 1994.

Evaluating the different passenger traffic systems, we distinguish between individual transportation that essentially consists of cars and motorcycles and public transportation with busses and trains and to an increasing extent also with aircrafts. The productivity or accomplished work of each single transportation system is described by the product of transported persons and distance, summed up as passenger kilometres, referring to the year considered.

Fig. 1-3 shows that the automobile (motorised individual traffic) plays a dominant role in the development of transportation performance of passenger traffic. Till the year 1988, the automobile's share in the total transportation performance of passenger traffic increased to 83.5% and then dropped slightly to 81.4% in 1995. The annual railroad transportation performance has remained rather constant over many years; its share has been continuously decreasing at the same time (1988: 5.7%). In the 90's, railroad again gained importance; its share once again amounted to 7% in 1995. This trend could be the same in the future if railroad's attractiveness increased. All current predictions expect a further rising need for mobility, which concerning economic and ecological basic demands should be covered by both the transportation systems, roads and railways.

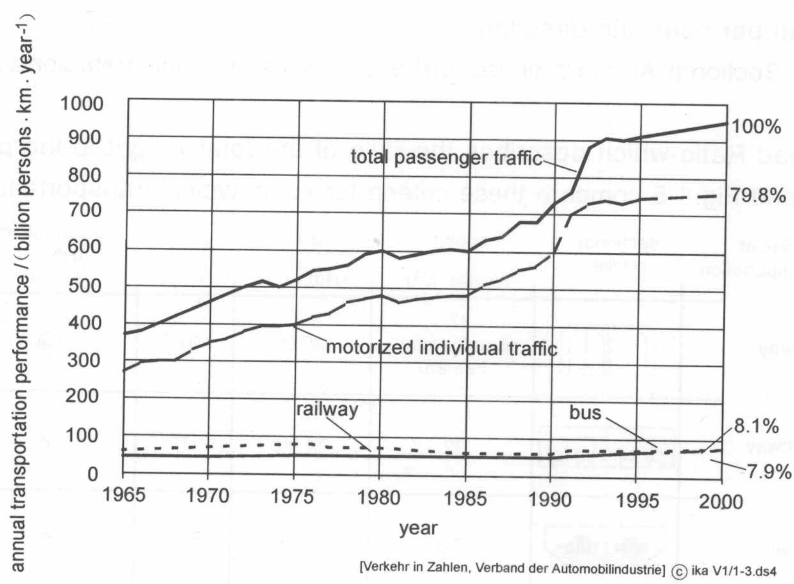

Fig. 1-3 Development of transportation performance in passenger traffic (Source: Verkehr in Zahlen 1996, VDA)

In order to evaluate the importance of the automobile correctly, it has to be pointed out that its value goes far beyond of being just a pure traffic system. For the majority of automobile customers, social aspects such as image and prestige as well as social acceptance play an important role. The vehicle's original purpose, safe transport of passengers and luggage, can thus take a backseat considering certain vehicles such as sports cars or convertibles. The sharp increase in models explains the various tasks a today's cars need to fulfil and where its specific advantage can be found as compared to other transportation systems.

1.1.1.2 Freight traffic

Freight traffic, in particular freight motor traffic, is subdivided by law into short-distance and long-distance traffic mainly because of fiscal reasons. According to the German "Güterkraftverkehrsgesetz" (§ 2 Abs. 2 GÜKG), the kind of freight traffic that covers distances within a radius of 50km (31miles) around the company site is referred to as short-distance traffic. Road traffic with commercial motor vehicles almost exclusively covers this so defined field of transportation.

For transportation of freight over long-distances, several different structured transportation systems are available:

Commercial vehicle, railroad, ship, airplane, and pipeline.

The following characteristic features allow a comparison of the transportation systems:

1) transportation Velocity-which is calculated on average considering the time for handling.

2) transportation Stream/Flow-as the amount of freight (mass or volume) that can be transported per hour and direction.

3) cross Sectional Area/Profile-as the area enclosed in the transportation system's profile.

4) payload Ratio-which describes the ratio of the total weight to the payload.

Fig. 1-4 and Fig. 1-5 compare these criteria for some typical transportation systems.

means of transportation	sectional profile	speed $v/(\text{mile}\cdot h^{-1})$	flow $\dot{v}/(m^3\cdot h^{-1})$	area A_p/m^2	transportation flow $v'=\dot{v}:A_p$
railway		32 (ohne Rangier-betrieb)	20.00	37	
highway		32	14.50	115	
canal		7.5	6.25	470	
pipeline	710	4.5	2.85	0.4	

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Fig. 1-4 Comparison of freight transportation systems

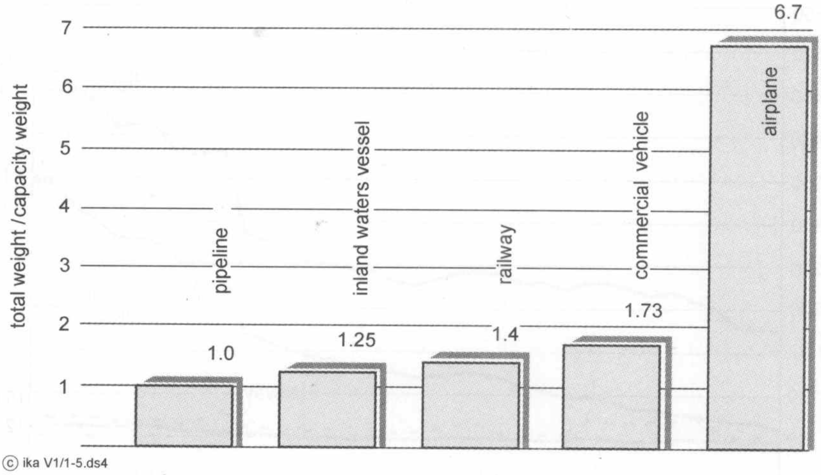

Fig. 1-5 Proportion of total weight to capacity weight for different transportation systems

This comparison shows that commercial vehicles and railways as compared to inland vessel and pipeline have higher transportation velocities and can thus manage correspondingly larger transportation streams. In contrast, the pipeline has the smallest profile area due to its construction and therefore achieves the largest transportation stream related to its cross sectional area.

The payload ratio, starting with the pipeline, inland vessel, railroad and finally the commercial vehicle, just slightly deteriorates (factor 1.7). The airplane, with respect to the payload ratio, however has a negative effect because in order to transport one ton of capacity weight, six tons of "dead weight" is required.

All systems are still being developed in order to improve the payload ratio by minimising the weight. A rise in technical standards, such as noise behaviour or safety of the motor vehicle make it even more difficult to carry out this task.

A transportation system's share in the total traffic performance depends on its suitability for certain major freight groups as well as on the total traffic volume of the different major freight groups. For example, the coal transport's share in the total amount of freight has strongly diminished and to some extent the railroad's transport performance has also become stagnant.

Fig. 1-6 shows the share of single transportation systems in the total freight traffic performance. Considering freight traffic, the continuously rising trend of the motor vehicle becomes obvious. Long-distance freight transport using commercial vehicles rose from 146billions t · km/a in 1993 to about 200billions t · km/a in 1995 and during the same period, the railroad transportation increased from 65 to about 70billion t · km/a. Presently, the percentage of both transportation systems in the total amount of traffic (short-and long-distance freight traffic) amounts to approx. 64% for commercial vehicles and 17% for railroads.

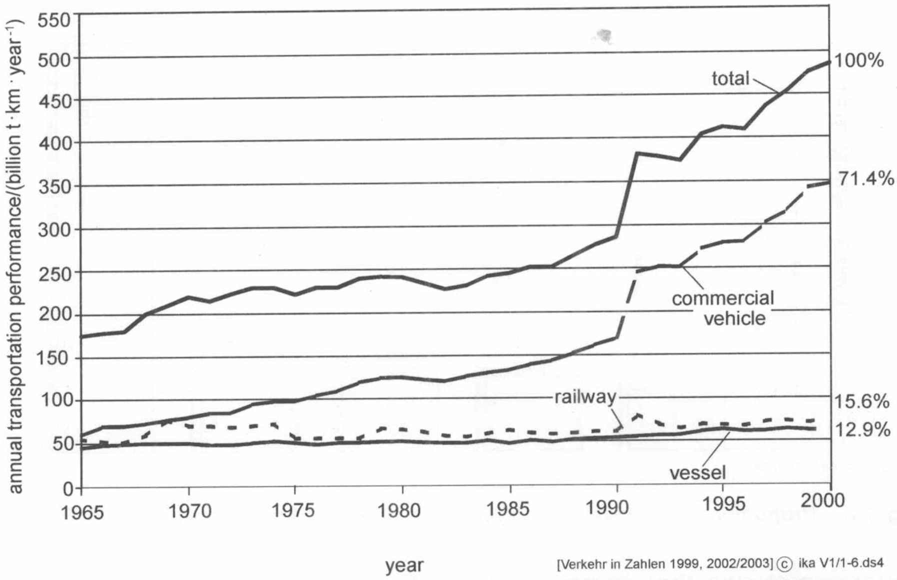

Fig. 1-6 Development of transportation performance in freight traffic
(Source: Verkehr in Zahlen 1996, 2002/2003)

The real advantage of long-distance road traffic is that it completely covers large areas without further expenses, while the railroad can only be efficient if large amount of traffic can be accumulated on fewer tracks. For this specific reason, attempt is being made for a strong integration of these systems thereby combining their specific advantages. The "rolling country road" represents an approach to achieve this aim. In this case, for certain track sections, entire trucks are loaded onto the railroads, which at the place of destination take over the further distribution of goods (e.g. transit over the Alps).

1.1.2 Energy demand

Till date, the development of traffic has been characterised by a distinct and constant rise in traffic performance, most of all in passenger traffic by means of motor vehicles. A reason for this is that the primary energy source for motor vehicles, crude oil, has been rather cheaply available and that too in sufficient amounts [1-2]. However, the steadily increasing road traffic performance goes hand in hand with rising negative side effects. A change in the essential basic conditions, e.g. concerning the availability of various resources, overlaps this performance.

The main objective of road traffic and motor vehicle future development would therefore be focussed on the continuous reduction of energy consumption, partial substitution of the primary energy source i.e. crude oil and the reduction of harmful effects on the environment.

Referring Fig. 1-7, we notice that the demand of primary energy in the Federal Republic of Germany is mainly covered by crude oil. The road traffic's share in the total demand for primary energy in the year 1993 amounted to 15.4%. By means of