SIMULATION

OF

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China Communications Press

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图书在版编目（CIP）数据

速度与油耗仿真基础/潘玉利著．—北京：人民交通出版社，2005.12
ISBN 7-114-05891-8

Ⅰ.速…　Ⅱ.潘…　Ⅲ.汽车-行车速度-关系-燃料消耗-研究-英文　Ⅳ.U471.23

中国版本图书馆CIP数据核字(2005)第155295号

书　　名：SIMULATLON OF VEHICLE SPEED AND FUEL CONSUMPTION
著 作 者：潘玉利(YULI PAN)
责任编辑：毛　鹏
出版发行：人民交通出版社
地　　址：(100011)北京市朝阳区安定门外外馆斜街3号
网　　址：http://www.ccpress.com.cn
销售电话：(010)85285838,85285995
总 经 销：北京中交盛世书刊有限公司
经　　销：各地新华书店
印　　刷：北京凯通印刷厂
开　　本：787×980　1/16
印　　张：17.5
字　　数：281千
版　　次：2005年12月第1版
印　　次：2005年12月第1次印刷
书　　号：ISBN 7-114-05891-8
定　　价：108.00元

Preface

Vehicle speed and fuel consumption are the essential factors for highway network planning, feasibility study, geometry design and road asset maintenance and management. Investigations into vehicle speed and fuel consumption include the Caribbean, Kenya, Brazil and India studies, which resulted in the World Bank's HDM-III highway design and maintenance standards model in the 1980's, and the recent research conducted in Australia, the result of which is employed in the HDM-4 highway development and management model. The literature highlights that attention to the investigation of vehicle speed and fuel consumption can be traced back to the early 20 century. Since the 1920s, considerable efforts have been paid to the study of tradeoffs amongst vehicle speed, fuel consumption, road geometry and pavement condition.

Statistical information shows that the majority of trucks and buses in the PRC are petrol powered, which is expected to have a different behaviour in speed and fuel consumption to those of diesel engines. To find the difference due to the two types of engines, an extensive study into vehicle speed and fuel consumption is conducted based on field speed and fuel consumption experiments and computer simulations. This book presents a description of the methodology, experiments and models developed for the simulation of vehicle speed and fuel consumption for highway economic analysis..

The book is in 10 chapters and 4 appendices. Chapter 1 presents the background to the issues tackled. Chapters 2 and 3 review major vehicle speed and fuel consumption studies conducted over the past 3 decades. Chapters 4 and 5 present detailed descriptions of experiments carried out for vehicle speed and fuel consumption collection. Chapter 6 is a description of free speed modelled on the basis of the World Bank's HDM-III and HDM-4 steady state speed model. Chapter 7 describes the speed-flow relationships developed for both motorised traffic and non-motorised traffic. Derivation and calibration of the mechanistic fuel consumption model is presented in Chapter 8 followed by a detailed model feature examination. Chapter 9 provides a methodology for fuel consumption simulation on the basis of information of engine maps and the mechanistic fuel consumption model developed in Chapter 8. Chapter 10 discusses a computer model for simulating the effect of changes of vehicle and road characteristics on vehicle speed and fuel consumption. The appendices concern: A. Plots of the field fuel consumption results; B. Plots of engine speeds; C. Plots of the engine map based fuel consumption; D. Simulation of vehicle speed and fuel consumption.

Acknowledgements

The information of vehicle speed and fuel consumption forms the basis of the database for the modelling and calibration of models, theories and methodologies of vehicle speed and fuel consumption of the PRC study. The costly field vehicle speed and fuel consumption experiments and data analysis are financially and technically supported by several organisations and individuals, to whom the author would like to express his sincere gratitude:

Ministry of Communications (MOC), PRC
Shandong Provincial Highway Administration Bureau (SDHAB)
Jilin Provincial Highway Administration Bureau (JLHAB)
Anhui Provincial Highway Administration Bureau (AHHAB)

Mr. Guojing CHEN, Research Institute of Highways, MOC, PRC
Mr. Songgen WANG and Mr. Hai LIU, SDHAB
Mr. Qun GAO, JLHAB
Prof. M.S. Snaith, the University of Birmingham, U.K.
Dr. H.R. Kerali, the World Bank

All engineers who contributed to the Data Collections

Several sections of this book are prepared based on the ninth five-year national key research programme: *Development of an Investment Benefit Analysis System for China Highways* and partially on the basis of the author's PhD thesis submitted to the University of Birmingham of the United Kingdom. Thanks therefore to:

Research Institute of Highways of the Ministry of Communications, PRC
The University of Birmingham, UK

About the Author

Yuli PAN has been engaged for the past 20 years in the research, development and implementation of road asset management systems including data collection systems at the Research Institute of Highways of the Ministry of Communications. He is currently research Professor of the PRC Research Institute of Highways and member of the Experts Committee of the Ministry of Communications, PRC.

Contents

1 Introduction

1.1 Objective of the Book

The objective of this book is to present a methodology for the simulation of vehicle speed and fuel consumption. Attention is paid to the development of free speed, speed-flow relationships and fuel consumption models on the basis of extensive literature review, field experiments and laboratory tests. An integrated simulation model is developed for the purpose of simulating vehicle speed and fuel consumption for different types of vehicles by varying values of road geometry, pavement condition, traffic flow and flow composition.

The book consists of the following major contents:

——Review of vehicle speed
——Research into fuel consumption
——Speed collection
——Fuel consumption experiments
——Free speed
——Speed-flow relationships
——Development of mechanistic fuel consumption models
——Engine map based on fuel consumption models
——Simulation of vehicle speed and fuel consumption

1.2 Background to the Issue Tackled

The highway network in the PRC has been considerably extended and improved in the past two decades. In comparison, vehicle population has shown even higher growth rate due to the quick development of the country's economy. The quick growth in vehicle population increased the pressure on the highway network, which carried over 75 percent of cargo transport and 85 percent of passenger transport (MOC, 1990—2000). The unbalanced development of highway network and vehicle fleet led to an incessant shortage of road space, traffic congestion and rapid deterioration of pavement.

To improve the highway network, it requires a huge amount of investment, but funding is always a pivotal problem. In order to use the scarce and limited investment, highway projects should be appraised and evaluated in economic standards and models, such as the Word Bank's highway design and maintenance standards model (HDM-III; Watanatada et al. 1987a) or the HDM-4 highway development and management model.

As part of highway economic evaluation, considerable efforts have been made to develop and calibrate the relationships employed in the economic appraisal models, including the Caribbean (Morosiuk and Abaynayaka, 1982), Kenyan (Hide et al, 1975), Brazilian (Watanatada et al, 1987a) and Indian (CRRI, 1982) studies, which contributed a great deal of knowledge to the understanding of relationships of vehicle speed and fuel consumption. The literature review result indicates that vehicle speed and fuel consumption relationships are the most important factors for highway economic appraisal and evaluation.

As pointed out by Hine and Chilver (1991), the major relationships employed in HDM-III that developed based on the Caribbean, Kenyan, Brazilian and Indian field experiments, are different and large variations exist between the predictions. Since the vehicles employed in the HDM-III, HDM-4 and other models are different from the petrol engine powered trucks and buses that predominate the PRC traffic streams, simple local adaptation of the above relationships may lead to incorrect estimations. Therefore, development and calibration of vehicle speed and fuel consumption relationships for the PRC petrol vehicles should be performed.

1.3 Methodologies for Speed and Fuel Consumption

1.3.1 Free Speed and Speed-Flow Relationships

The literature review of major speed prediction models highlights that free speed models can be developed by using the multiple regression technique or mechanistic relationship. The former demonstrates high reliability, but suffers a drawback of local adaptability; the later defines coefficients of the model with clear physical meanings, which is convenient to calibrate to local conditions but requires a good theory for model development.

Motorised and non-motorised traffic flow are fundamentally different in terms of traffic behaviour, therefore they should be separately treated. The literature indicates that speed-flow relationship is a common method for modelling the effect of congested traffic.

1.3.2 Fuel Consumption Models

A number of methods can be applied to the development of fuel consumption relationships including engine map, mechanistic model and data regression. The data regression model although having high reliability, cannot be reliably extrapolated. The engine map, which is usually produced based on laboratory engine tests, is a cheap way of modelling but requires a good fuel consumption theory. The mechanistic model that is derived from energy, force or power balance relationships should be an ideal method for it has been successfully used in many fuel consumption studies.

In order to validate the fuel consumption models proposed for the PRC vehicles, a large field fuel consumption experiment was carried out supplemented by laboratory engine tests, which covered major types of vehicles and a wide range of road characteristics. Both speed and fuel consumption relationships are investigated for free flow and congested traffic flow.

1.4 Database

1.4.1 Speed Relationships

The modelling of free speed and congested speed relationships requires a great deal of speed information. For the purpose of speed modelling, a vehicle speed and traffic flow observation experiment is designed and conducted on various selected road sections. To reflect the effect of non-motorised traffic flow on vehicle speed, speed and traffic flow observations for non-motorised traffic is conducted. The experiment is performed to collect speeds with and without the influence of non-motorised traffic flow.

Hourly flow is a major variable affecting vehicle speed. In order to produce hourly flow distribution models, traffic flow data is collected from 14 permanent traffic count stations, each of which consists of 8760×11 individual traffic flow data.

1.4.2 Fuel Consumption

Fuel information is required for the validation and calibration of the proposed mechanistic fuel consumption models. To obtain fuel consumption data, a controlled field fuel consumption experiment is conducted for 9 types of vehicle including light petrol trucks, medium petrol trucks, heavy diesel trucks, medium petrol cars, medium petrol buses, large petrol buses, petrol trailers, medium petrol jeeps and small petrol pickups. The experiment is mainly carried out in Shandong province (35 selected road sections, 5 types of vehicles) and partially in Anhui province as a complement (20 selected road sections, 4 types of vehicles). As a result, 1568 sets of fuel consumption data are obtained in Shandong province and 491 sets in Anhui province.

1.5 Free Speed

Individual effects of road characteristics, including road geometry and road roughness, on vehicle speed are considered in the free speed models based on mechanistic analysis and free speed observations.

The free speed analysis indicates that: 1) desired speed varies with both vehicle performance and road width; 2) vehicle speed is not affected by road gradient for small negative downhill roads, instead, it is dominated by desired speed when the negative gradient is less than 4.5 percent; 3) road roughness affects vehicle speed only when it is rough enough to make the drivers feel uncomfortable and cause damage to vehicle parts. The critical point is estimated at about *IRI* 7 m/km varying with vehicle types; 4) the combined effect of road characteristics is estimated by using the HDM-III/HDM-4 probabilistic limiting velocity model. The Weibull distribution shape parameter β obtained in the PRC speed study is higher than the Brazilian study and lower than the Indian observations.

1.6 Speed-Flow Relationships

A general speed prediction model, which reflects both free speed and congested speed, is developed on the basis of the knowledge of free speed models, speed-flow relationships and non-motorised traffic effect relationships. The free speed model shows a function of engine power, road curvature, road gradient, road roughness and desired speed.

The congested speed including speed-flow relationships and non-motorised traffic effect relationships presents linear behaviour. The slopes of the speed-flow curves vary between -0.0052 and -0.0331 depending on the road characteristics and vehicle type. It is found that the slope of non-motorised flow effect relationships varies with both vehicle type and non-motorised traffic volume, but is almost independent of motorised traffic flow.

Road capacity is estimated between 1200 veh/h and 4500 veh/h with corresponding capacity speed ranging from 28 km/h to 35 km/h. The effect of road width on both vehicle speed and capacity is significant. A road with double the width of pavement will have a road capacity much more than twice the single width pavement. Road capacities for other terrains are estimated using a capacity-free speed relationship.

Hourly flow distribution models are developed for major types of roads, which suggest that both distribution of hourly flow as a percentage of the AADT and traffic flow composition are constant irrespective of road type and time of year. The curves of hourly flow distributions can be divided into 5 groups, each of which is distinct in traffic flow. The average hourly flow as a percentage of AADT and AADNT ranges from 0.5 to 8.59 and 0.36 to 5.69 respectively.

1.7 Estimation of Fuel Consumption

1.7.1 Theoretical Fuel Consumption Models

Fuel consumption models and engine speed relationships are developed for each type of vehicle. The mechanistic fuel consumption model, which is validated from fuel consumption experiments, shows a function of engine power requirement and engine speed. A high quality of regression is achieved with R-square ranging between 0.95 and 0.99 except for the car Santana, which is only 0.40.

The empirical engine speed relationship, which is a function of vehicle speed, is established for 9 types of vehicle based on the experimental results. When vehicle speed reaches 60 km/h, the vehicle is assumed to travel in top gear.

Vehicle speed is a sensitive variable in the proposed mechanistic fuel consumption models. Amongst the road factors, road gradient has the most significant effect on fuel consumption followed by road roughness and rolling resistance. The effect of road curvature including air resistance is not significant before high speed is reached.

1.7.2 Engine Map Based on Fuel Consumption Models

As experienced by many highway engineers, controlled field fuel consumption experiment is a labour intensive, time consuming and costly method for data acquisition. Although the field fuel consumption experiments can produce reliable results, investigators sometimes prefer to use engine maps due to its low cost for fuel information data collection and a reasonable accuracy in estimation of fuel consumption.

The engine map based on fuel consumption prediction relationship is developed based on the mechanistic fuel consumption model and the information of engine maps for 17 different types of engine. A coefficient designed to reflect the difference in fuel consumption between laboratory engine test and field fuel consumption experiments is introduced.

1.8 Simulation of Vehicle Speed and Fuel Consumption

An integrated simulation model is developed for the purpose of simulating vehicle speed and fuel consumption as shown in Figure 1.1. The model can be used to predict free speed, congested speed and fuel consumption for 26 different types of vehicles, three different laden levels and various highway and traffic conditions including pavement width, road gradient, road curvature, road roughness, traffic flow and traffic composition.