INFLUENCE OF RAINFALL ON THE CAPACITY OF SINGLE CARRIAGEWAY IN MALAYSIA

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To my family for enduring my absence during the course of this study and my mum who said “may all be well with you”, as I departed to Malaysia.

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ABSTRACT

Traffic flow disturbances come from intersections, on/off ramps, work zones, pavement distress sections, tapering sections and ambient conditions. These cause speed drops and traffic flow rate changes and impact on the traffic carrying ability of roadway sections. These disturbances generate queues, cause long delays, increase travel times and may result in accidents. All these causes and effects must be considered if highway facilities should be operated unhindered. Thus this thesis examines the problems of rainfall disturbance to traffic flow and highway capacity. The effect of rainfall is more severe in tropical regions where it occurs in large quantities throughout the year. Thus four sites were set up in east and south Malaysian Peninsula respectively to generate data for the study. Data was collected using automatic traffic counters and rainfall data was obtained from two surface rain gauge stations that were 1174m and 1840m away from the data collection sites. The empirical data pointed towards speed and traffic flow reduction during rainfall spells. Further analysis using the fundamental diagram (trapezoidal flow contraction) method confirmed speed and flow reduction as the main impacts of rainfall to traffic flow in adverse weather. For the scenarios tested, such as peak period versus non-peak, the trend remained the same. However, peak hour flow conditions are associated with instabilities that are difficult to separate from rainfall disturbances and were not analysed further. Highway capacity drops occurred between the dry condition and the three rainy regimes tested. Implications of traffic flow contraction for Passenger Car Equivalency (PCE) values of vehicles and traffic shock waves propagation were also investigated. PCE of heavy vehicles were lower than the values employed in the Arahan Teknik and the Malaysian Highway Capacity Manual, suggesting better performance of these vehicles under rainfall conditions mainly due to larger average headways and the prevailing free-flow conditions. In the case of traffic shock wave, the wave speeds were all lower than the speeds at critical density and the wave generated moved principally in the direction of the main stream flow, suggesting rarefaction waves rather than shock waves. The findings in this study could be incorporated into a wider strategy (Intelligent transportation system) to inform and assist drivers in inclement weather.

ABSTRAK

Ganguan aliran trafik adalah berpunca daripada persimpangan, keluar/masuk tanjakan, zon kerja, bahagian kesukaran turapan, dan keadaan persekitaran. Ini menyebabkan kelajuan menurun dan kadar aliran trafik dan kesan terhadap trafik yang mempengaruhi keupayaan bahagian jalan. Gangguan-gangguan ini menyebabkan kesesakan, kelambatan yang panjang, pertambahan masa perjalanan dan mungkin akan menyebabkan kemalangan. Semua penyebab dan kesan ini mesti dipertimbangkan jika kemudahan lebuhraya yang perlu dioperasikan tidak terganggu. Oleh itu, tesis ini memeriksa masalah gangguan hujan kepada aliran trafik dan muatan lebuhraya. Kesan hujan adalah lebih teruk di rantau tropik di mana ia berlaku dalam kuantiti yang besar sepanjang tahun. Oleh itu, empat tapak telah dibina di Timur dan Selatan Semenanjung Malaysia masing-masing, untuk memperoleh data bagi kajian ini. Data telah dikumpul menggunakan pembilang trafik automatik dan data hujan telah diperoleh dari dua stesyen tolok hujan permukaan pada jorak 1174m dan 1840m dari tapak pengumpulan data. Data empirik menunjukkan pengurangan kelajuan dan penguncupan aliran trafik berlaku semasa hujan turun. Analisis tambahan menggunakan kaedah rajah asas (penguncupan aliran trapizoid) menyokong pengurangan dan penguncupan aliran laju merupakan kesan utama hujan terhadap aliran trafik dalam cuaca buruk. Bagi semua senario yang diuji, seperti tempoh puncak melawan tempoh bukan puncak, kecenderungannya kekal sama. Walau bagaimanapun, keadaan aliran masa puncak dikaitkan dengan ketidakstabilan yang sukar untuk memisahkan gangguan hujan dan mengurangkan keadaan aliran yang bukan masa puncak. Penurunon muatan lebuhraya berlaku di antara keadaan kering dan tiga rejim hujan diuji. Implikasi penguncupan aliran trafik bagi nilai kenderaan *Passenger Car Equivalency* (PCE) dan gelombang kejutan trafik juga disiasat. PCE kenderaan berat adalah lebih rendah daripada nilai piawai yang digunakan dalam Malaysia, menyarankan prestasi yang lebih baik kenderaan ini di dalam keadaan hujan yang disebabkan oleh gerakan maju purata yang lebih besar dan keadaan aliran bebas. Dalam kes gelombang kejutan trafik, laju gelombang adalah lebih rendah daripada laju pada ketumpatan kritikal dan gelombang yang dihasilkan telah bergerak dalam arah aliran utama, menyarankan penggunaan gelombang penghalusan daripada gelombang kejutan. Dapatan dalam kajian ini mungkin digabungkan dengan satu strategi yang lebih meluas (Sistem Pengangkutan Pintar) bagi memberitahu dan membantu pemandu dalam cuaca buruk.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ADT	-	Annual Daily Traffic
ATC	-	Automatic Traffic Counter
FD	-	Fundamental Diagram
FHWA	-	Federal Highway Administration
GQM	-	Generalised Queuing Model
HCM	-	Highway Capacity Manual
HGV	-	Heavy Goods Vehicle
JKR	-	Jabatan Kerja Raya
LGV	-	Light Goods Vehicle
LOS	-	Level of Service
MHA	-	Malaysian Highway Authority
MMD	-	Malaysian Meteorological Department
PC	-	Passenger Car
PCE	-	Passenger Car Equivalent
pdf	-	Probability Density Function
SMS	-	Space Mean Speed
SPM	-	Semi-Poisson Model
SSD	-	Stopping Sight Distance
TRB	-	Transportation Research Board
TMS	-	Time Mean Speed
UAP	-	Urban All-Purpose Road
WMO	-	World Meteorological Organization

LIST OF SYMBOLS

h_m	-	Mean Traffic Stream Headway
H_{ij}	-	Headway of Vehicle Class *i* under condition *j*
q	-	Flow or Volume
k	-	Traffic Density
v	-	Traffic Speed
q_c	-	Traffic Capacity
F(x)	-	Cumulative Distribution Function
f(x)	-	Probability Density Function
R(t)	-	Reliability Function
PCE_i	-	Passenger Car Equivalent of vehicle Class i

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Overview

Traffic flow rate changes are common occurrences on road transportation networks'. They may refer to disruptions to traffic flows that could result in speed reduction, bottlenecks and queue formation. In extreme situations congestion forms and accidents may occur. Traffic flow rate changes result when a roadway section is unable to accommodate traffic flows due to reduction in section geometry, or a traffic surge from entrance ramps or deceleration of vehicles at an exit ramp or poor roadway conditions. All of these may be due to the roadway system. Disturbances external to the roadway system also influence traffic flow rates and are known to cause similar effects. These include ambient conditions particularly the weather. Among the weather elements rainfall has the most dramatic effect on traffic flow rate changes.

This thesis presents research carried out to investigate the influence of rainfall on highway capacity along principal roadway segments. The basis for this research is to see what impacts rainfall has on traffic flow and to establish whether highway capacity changes occur and to what extent. Using the fundamental diagram approach, traffic scenarios for dry weather and rainy periods will be modelled and compared to see the impact of rainfall on highway capacity. Further to this, we will investigate the implications of highway capacity changes due to rainfall on passenger car equivalency (PCE) of vehicles and traffic flow shock wave propagation.

This introductory chapter is organised as follows. In Section 1.2 the background to the research problem is given. Section 1.3 presents the main problem formulation for this thesis. In Section 1.4 the objectives are stated while in section 1.5 the scope of the research is described. The contributions of the thesis to the state of the art of traffic studies in adverse weather are discussed in Section 1.6., and the research relevance is stated in section 1.7. The setup of the thesis is outlined in section 1.8.

1.2 Background to the Research Problem

The determination of roadway flow rate is one of the main outputs in traffic studies and traffic theory analysis. Its maximum attainable value as defined in the Highway Capacity Manual (TRB, 2000) is a key input in the assessment of current roadway usage, facility selection, design and rehabilitation. Highway capacity values have traditionally been regarded as deterministic. Meaning a single high value above which roadway segments cannot cope. However, measurements of highway capacity reported in the literature reveal variations in the value of capacity for similar traffic conditions and roadway segments. Since highway capacity is central to roadway performance interest has grown in the evaluation of capacity for different traffic scenarios with a view to improving the strategies in dynamic traffic management.

Increase in congestion in towns and cities coupled with a need for fast and incident free traffic flow calls for real time monitoring of traffic flows. Further to this, weather systems cause widespread disruptions to transportation systems in many parts of the world. In tropical regions, rainfall disturbances to traffic flow are common. Studies on traffic capacity in normal weather are well documented but remain limited in adverse weather. In particular, the issue of highway capacity variability and extent under rainfall conditions are scanty. Quantifying the effects of rainfall on highway capacity is the first step towards comprehensive dynamic traffic management in adverse weather.

1.3 Problem Formulation

The need to curtail congestions on highways calls for real-time monitoring, surveillance and control of road networks. Traffic flow disturbances in urban areas due to traffic, roadway and control conditions in normal weather are continually being addressed but attention is yet to focus on disturbances caused by adverse weather. Rainfall in particular causes serious disturbances to traffic flow and contributes to poor visibility, reduction in sight distance, slippery surfaces, drag forces, anxiety, increased journey times, delays, and breakdown of the flow.

Traffic studies under general adverse weather conditions have centered on vehicle crashes FHWA, (2008); safety Edwards, (1998); road hazards Andrey et al., (2003a) and traffic accidents Zhang *et al*., (2005). Studies on the impact of rainfall on traffic flow variables include Unrau and Andrey, (2006) and Aggarwal *et al.* (2006). Countries in tropical and monsoon climates are being continually subjected to rainfall throughout the year. Motorists in these countries have become accustomed to driving in rainfall with its attendant consequences. Studies on the effect of rainfall on specific traffic variables such as headways Hogema, (1996) and capacity Chung *et al*., (2006); Chung *et al*., (2005b); and Keay and Simmonds, (2005) have also been reported. Furthermore, Chung *et al*., (2006) and Billot *et al*., (2008) have discussed rainfall intensity changes on capacity.

Besides the variability in the contexts of the earlier studies, no study has used the fundamental diagram approach and rainfall data from surface rain gauge stations. The fundamental diagram approach enables a complete description of the traffic state thus gaining more clarity on traffic behaviour in adverse weather. Surface rain data on the other hand, reflects the interaction between drivers and the rain at road level.

1.4 Research Objectives

The research presented in this thesis seeks to evaluate highway capacities in dry weather as well as in rainy weather conditions. It can be argued that the disturbances from rainfall induce a flow contraction. Since flow contractions are sources of instabilities on highways, prolong rainfall or variation in its intensity may cause further flow contractions. Efficient approaches to traffic management in adverse weather therefore calls for anticipation of future traffic conditions. The objectives of this thesis are:

i. To examine the extent of rainy conditions per surveyed road length.
ii. To evaluate the capacity of road section under daylight and variable rainy conditions.
iii. To evaluate the road capacity loss resulting from variable rainfalls under daylight conditions; and
iv. To determine the effects of variable rainfalls on traffic kinematic waves.

1.5 Scope of the Study

The scope of the thesis includes:

i. Generation of empirical traffic flow data from the selected sites.
ii. Acquisition of high resolution rainfall intensity data close to the selected sites.
iii. Sorting of traffic flow data into rainfall intensity categories of light, moderate and heavy.
iv. Assignment of passenger car equivalent values obtained from the "Arahan Teknik" to convert traffic volume and density values from vehs/hr to pce/hr.
v. Plot of the flow-density data to obtain the quadratic functions for traffic capacity prediction.
vi. Evaluation of the roadway capacity using the quadratic functions and comparing to see the changes in capacity between the dry weather and the rainy conditions.
vii. Evaluation of passenger car equivalent values using the empirical data obtained from the selected sites.
viii. Evaluation of capacity using the modified passenger car equivalent values.
ix. Evaluation of capacity losses from the modified PCE values.

x. Evaluation of the wave speed and direction resulting from the capacity losses in the earlier evaluations.

1.6 Thesis Contributions

This thesis contributes to the state-of-the-art in modelling traffic flow during rainfall. It uses a unique modelling approach (trapezoidal flow rate contraction method) and hence enriches the literature with this method. It further enriches the literature by providing novel information on highway capacity changes in wet weather and then elucidates on the issue of modified passenger car equivalent values. Traffic flow shock wave which has hitherto not been considered under rainfall conditions is also a novel contribution to the literature. The fundamental diagram method can be extended to cover multiple conditions at the same time.

1.7 Research Relevance

There are a number of wet weather studies on roadways outside Malaysia. However, the extent of variable rainy conditions on roadway capacity, has neither been fully explored, nor well understood. Often passenger car equivalent values are broadly applied to all conditions. This study is a first attempt to look into the extent of capacity loss resulting from rainy conditions in Malaysia and organised in a way, which offers results based on a synthesis of aggregate roadway capacity and rainfall data. Its significance is in its attempt to show that by mapping out specific areas where action is needed roadway capacity loss resulting from rainy conditions can be reduced.

The research has relevance for traffic management policy and decision making process. The findings in this thesis can be incorporated into a wider strategy for dynamic traffic management in adverse weather conditions. Predicted capacity can be used for scenario building for traffic management in both normal and wet weather conditions. The modified PCE values can point to overestimation or underestimation of capacity values on specific sites and conditions. With this method, it is easy to see if traffic shock wave will pose a problem to traffic flow in adverse weather.

1.8 Thesis Outline

This section provides an outline of the thesis and gives brief information about each chapter. Chapter 2 presents a literature review on highway capacity. The theoretic arguments, empirical capacity estimation methods, disturbances to general highway capacity, inclement weather conditions and their relationships with capacity, passenger car equivalency values and traffic shock waves are all covered in this chapter. Chapter 3 is based on highways and traffic in Malaysia. The highway systems in Malaysia are discussed in the context of this thesis. In particular, the underlying assumptions of driver behaviour under rainfall and operations on the roadways are presented. Chapter 4 is on data collection. It gives the criteria for site selection, assessment of the selected sites, the survey method employed, and the site set up, processing of data, analytical framework and hypothesis testing. Chapter 5 presents the empirical results such as the flow profiles, the dispersion plots, traffic volume and speed. Chapter 6 is on highway capacity analysis using the Arahan Teknik PCE values and the resulting fundamental diagram functions of flow-density. The traffic state parameters on the existing and predicted states as well as the hypothesis testing of the capacity values are presented. Chapter 7 is on Evaluation of modified PCE values. The effect of the modified PCE values on highway capacity and a hypothesis testing are also presented. Chapter 8 focuses on the applications of modified PCE. Chapter 9 is the concluding chapter and gives some research directions for future studies.

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