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Special Issue Green Transport

PREFACE

Dear Readers,

Welcome to the fourth issue of the JOURNAL OF SOCIETY for TRANPORTATION and TRAFFIC STUDIES, a new international peer-reviewed on-line journal. Four issues of the journal are published annually. This issue focuses on topics relating to traffic engineering. It includes 2 papers on the systematic preparation of traffic signal and roundabout design guidelines for application in Thailand, a Euro- Thai collaborative road safety action research project; a paper on an experimental study of the impact of traffic sign upstream of curves on two-lane highways; and a paper on the calculation of stress-strain, and deflection of pavement. The special issue covers the timely topic of green transport with a paper presenting the use of mathematical analysis to assess the impact of Indonesian government’s vehicle inspection and maintenance (I/M) measure to control the level of vehicle emission. An extensive 2- year vehicle emission data for 10 cities in Indonesia were used in the study. A preliminary assessment of the impact of the inspection and maintenance program indicates that key vehicle characteristics such as vehicles running kilometer per year, fuel system injection, and engine size capacity are significant in determining if a vehicle pass the I/M test. The authors suggest that citizens should be made more responsible in their urban lifestyle and thus to contribute to the goal of low carbon society; they should be fully responsible in looking after their vehicles by doing regular and routine maintenance and repair to help reduce the vehicle emissions.

I trust you will enjoy reading this issue and benefit from the information and findings in the papers.

Pichai Taneerananon
Professor

Chair of Editorial Board

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General Issue

TRAFFIC CONTROL AT SIGNALIZED INTERSECTIONS – PREPARATION OF A DESIGN GUIDELINE FOR THAILAND

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Abstract: Traffic control by traffic signals is successfully applied at intersections around the world. Methods and parameters used are mostly quite similar but in some cases there are essential differences which have a significant impact on road traffic safety as well as on traffic flow. Especially in emerging and developing countries, there is often the problem that knowledge in the design of road infrastructure and traffic control – like traffic control at signalized intersections – is not available for road designer and engineers in the design process or is not adapted to national conditions and requirements. These problems are oftentimes the main reason for existing deficits in the design of road infrastructure with respective impact on road traffic safety as well as on traffic flow.

In the Thai-EC project “Improving Road Traffic Safety in Thailand – A Common Challenge for European and Thai Universities” the network partners of “NICE on RoadS” want to improve the current situation in Thailand, by preparing and implementing a guideline for the design of traffic control at signalized intersections.

This paper gives an overview of selected methods and parameters in the design of traffic control at signalized intersections, applied in Europe and Thailand. Based on a comparison, some methods and parameters are discussed and hints are given - how to improve current situation in Thailand. Finally an overview about the scale of planned field studies is given which will be conducted in Thailand in order to prepare a design guideline for Thailand and to adapt the planned guideline to Thai conditions and requirements.

Key Words: signal control, road traffic safety, guideline, NICE on RoadS

1. INTRODUCTON

Traffic control by traffic signals is successfully used for traffic control at signalized intersections inside as well as outside built-up areas around the world. Especially at high level sections of the road network signalized intersections are applied with the key objective of serving traffic volume on a high quality level. However, in addition to the quality of traffic flow, exhaust emissions and noise emissions – especially road traffic safety is a key aspect that needs to be addressed.

The design of signalized intersections covers the design of road infrastructure (intersection, road section,…) as well as the design of traffic control (control strategy, signal program,…). The focus of this paper lays on the second aspect – the design of traffic control at signalized intersections.

In general, design methods and parameters in the field of traffic control at signalized intersections are quite similar in European countries and in Thailand. But in some cases there are basic differences which have a significant influence on the quality of the mentioned aspects and here especially on road traffic safety.

Whereas in most European countries design engineers have generally the possibility to apply actual research results and findings in the design of traffic control at signalized intersections, because comprehensive design knowledge (e.g. design methods, parameters,…), adapted to national conditions, is available in design guidelines, recommendations and research reports (cf. Vesper et al., 2010). Thai design engineers do not have such a possibility because design knowledge in the field of traffic control at signalized intersections is only partly available in Thai design guidelines and recommendations. And if they are available, they are often not adapted to national conditions and not available in Thai language.

The partners of the international network “NICE on RoadS” want to improve the current situation in Thailand. They are preparing a design guideline for the “Design of traffic control at signalized intersections” for Thailand by application of the “Methodology for Design Guideline Implementation in Thailand – Based on International Technology and Knowledge Transfer” (cf. Vesper et al., 2010). The authors are sure that the planned guideline will close the existing gap of knowledge in the design of traffic control at signalized intersections in Thailand in the future. Furthermore it is hoped that application of the mentioned methodology will foster the implementation of further design guidelines in the future, too.

This paper gives an overview of selected methods and parameters in the design of traffic control at signalized intersections, applied in Europe and Thailand. Based on a comparison, some methods and parameters are discussed and hints are given - how to improve current situation in Thailand. Finally an overview about the scale of planned field studies is given which will be conducted in Thailand in order to prepare the planned design guideline for Thailand and to adapt the planned guideline to Thai conditions and requirements.

2. TYPES OF INTERSECTION AND TRAFFIC CONTROL

Different types of intersection as well as different types of traffic control can be used to connect roads in the road network with each other. Here one can distinguish between different types of at-grade intersections like:

- X-junction,
- T-junction,
- Roundabout
  - mini,
  - compact,
  - large (not recommended),
- pedestrian crossings (separated).

Different types of traffic control are applied at at-grade intersections like:

- “no control”, also known as “priority to the main road” (applied e.g. in Thailand),
- “priority to the right” (applied e.g. in Germany and Hungary),
- yield sign control,
- signal control.

The type of intersection and the type of traffic control have to be selected in the design process of road infrastructure according to different general considerations like:

- function of the road in the network,
- coherence to traffic volumes,
- road traffic safety,
- capacity,
- environmental aspects and other considerations.

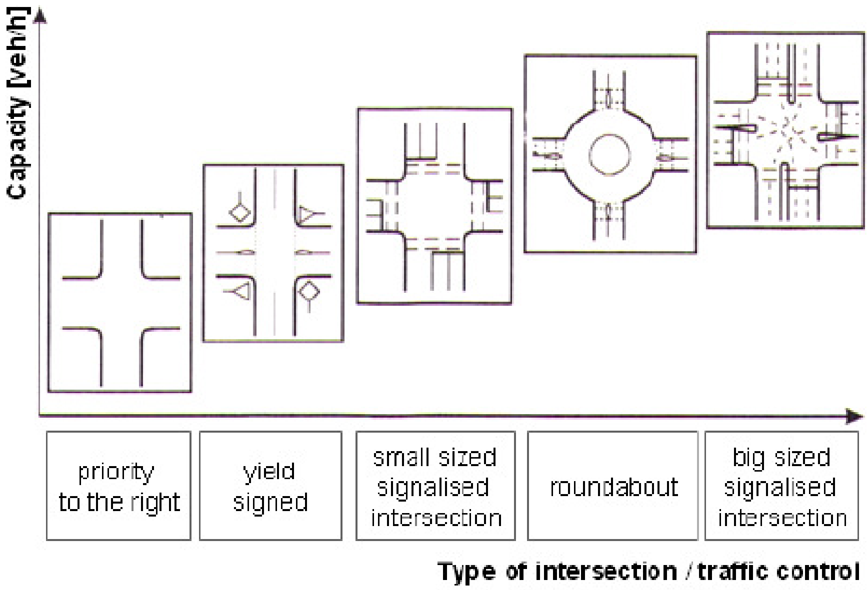


Figure 1. Capacity of different types of intersection and traffic control
Source: According to Schnabel and Lohse (1997)

The capacity of an intersection depends on its type as well as on the type of traffic control. The required capacity is an important criteria reason for selection of the type of intersection as well as of traffic control. In Figure 1, a qualitative estimation of the interrelation between capacity, type of intersection and type of traffic control is shown exemplarily.

Furthermore, the choice of the type of intersection and traffic control has a significant influence on road traffic safety. Accident cost rates (ACR) can differ significantly from each other as shown in Figure 2.

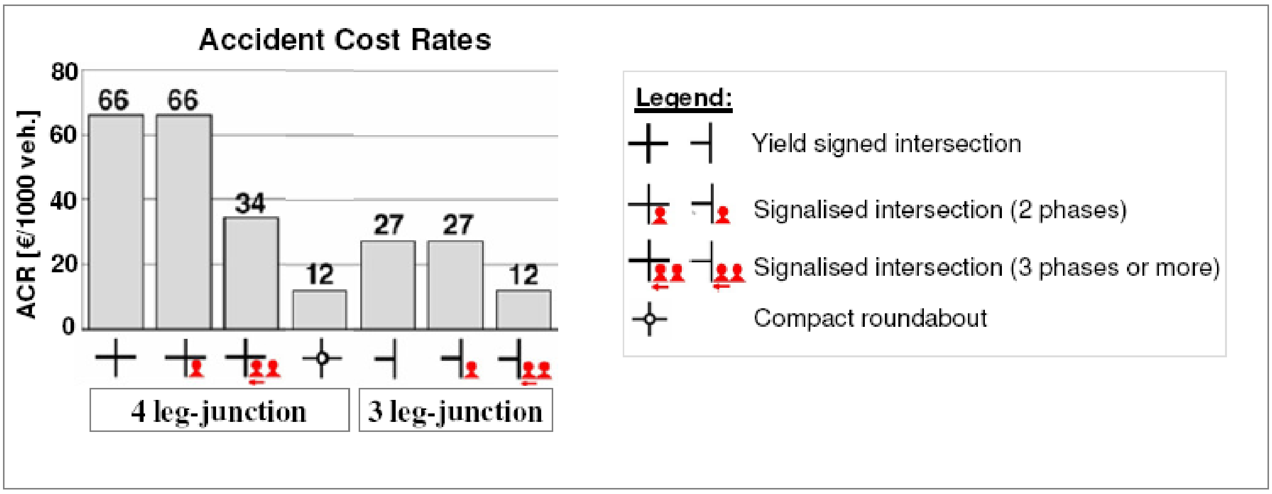


Figure 2. ACR of different types of intersection and traffic control applied on German highways; Source: According to Meewes (2003)

Signal control by traffic lights is recommended for application both inside as well as outside built-up areas in order to achieve different objectives like e.g…

- provision of high capacity,
- co-ordination of consecutively located intersections along a road section or in a road network,
- improving road traffic safety as blackspot treatment at intersections with existing design deficits like e.g.:
    - sharp crossing angle of connected roads,
    - overlapping swept-paths of traffic streams,
    - spacious intersection area.

At these intersections, the application of signal control can improve road traffic safety by better recognisability, visibility, understandability and driveability.

- giving priority to selected user groups in traffic control (e.g. public transport),
- protection of vulnerable road user groups (e.g. handicapped persons, pedestrians, cyclists),
- reduction of exhaust and noise emissions by reducing the number of stops and delays of motorised vehicles,
- etc.

3. DESIGN OF SIGNALIZED INTERSECTIONS

The design of signalized intersections can be subdivided in two parts - the design of road infrastructure and the design of traffic control. The focus in the design of road infrastructure lays e.g. on the design of road sections and intersections with the view on the design of horizontal alignment, vertical alignment, cross sections, markings and other elements of road infrastructure. Whereas the design of traffic control at signalized intersections focuses amongst others on the design of control strategies, signal programs and the design of required technical equipment to realise signal control in the road network as well as at local intersections.

Of course there is a strong interrelation between the design of road infrastructure and the design of signal control in the design process. In order to serve traffic volumes on a high quality level and here especially with the view on road traffic safety and traffic flow aspects, it is necessary, that the road design fits to the design of signal control and inversely.
As introduced in Chapter 1, the focus of the planned design guideline and respectively of this paper lays on the design of traffic control at signalized intersections as one part in the design of signalized intersections.

4. DESIGN GUIDELINES – STATUS QUO IN THAILAND AND EUROPE

In European countries rules and regulations for the design of traffic control at signalized intersections are normally defined in guidelines which are compulsory or partly recommendatory. If road and traffic engineers follow these rules and regulations, the design should have a high safety level.

German and Hungarian road engineers have for instance access to various design guidelines and recommendations which cover nearly all aspects of the design of road infrastructure. The selection of respective guidelines and recommendations, which need to be considered in the design process, depends mainly on the type of road, the subject of design and the affected road user groups by the planned road infrastructure. So in both countries at least one guideline deals with aspects of the design of traffic control at signalized intersections.

Thai road engineers have no such guidelines to follow because only a few national guidelines exist and relate to only a few topic areas. Even for topics where they are available, for most areas, no research based knowledge exists, which would adapt foreign guidelines or standards to national conditions. Instead of national guidelines, often guidelines from other countries like Japan, Australia or the United States are used and they are only available in foreign language and are not adapted to national conditions in Thailand. In many cases, road and traffic engineers, for lack of appropriate guidelines, have to design road infrastructure based only on individual decisions, assumptions or estimations which could be the reason for the inadequately designed roads especially from the point of road traffic safety.

Experiences of road safety audits and results of research projects executed by Thailand Accident Research Centre (TARC) confirm this statement especially in the field of traffic control at signalized intersections. There is therefore an urgent need to develop a national Thai guideline for the design of signal control at signalized intersections in order to provide research-based knowledge for Thai road designers and traffic engineers in the field of traffic control at signalized intersections.

In the following chapters some aspects in the design traffic control at signalized intersections will be discussed and some hints will be given to improve signal control in Thailand. It is planned that these hints will also be considered in the planned Thai guidelines.

5. CONTROL LEVEL

In general, two control levels can be distinguished in traffic control at signalized intersections in a road network, according to their areal coverage as follows:

- area control level (macroscopic level)
- local control level (microscopic level).

On the area control level, control strategies are defined which are effective for several signalized intersections located in an area, like e.g. in a road section, district or even a whole city.

Whereas the local control level comprises signal control at a local single intersection. Here local control decisions are only effective for road users crossing the respective signalized intersection.

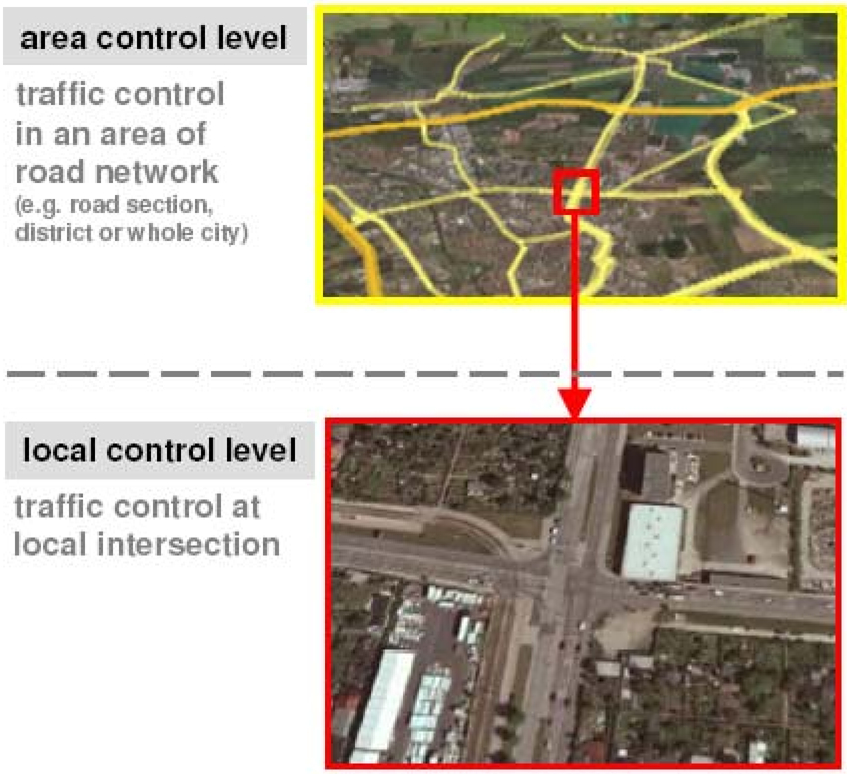


Figure 3. Areal sphere of area and local control level
Source: Vesper (2009)

If both control levels are implemented, the higher ranking control decisions will be made on the area control level. The control decisions of the area control level will be considered respectively in signal control at the local intersection on the local control level.

The areal coverage of both control levels is shown exemplarily in Figure 3.

5.1 Area control level

The main objective of the area control level is to adapt signal control of an area to changing traffic conditions over the day by selection and activation of different signal programs on the local control level.
The selection and activation of signal programs can be conducted alternatively time-dependent or traffic dependent as shown in Table 1.

Table 1. Control strategies on the area control level
Source: Vesper (2009) according to FGSV (1992)

Control strategies on the area control level		Activation of signal programs on the local control level	
General term	**Main characteristic**	**Time-dependant**	**Traffic Time-dependant**
Selection of signal program	**Time-dependant selection**	X	
	Traffic-dependant selection		X

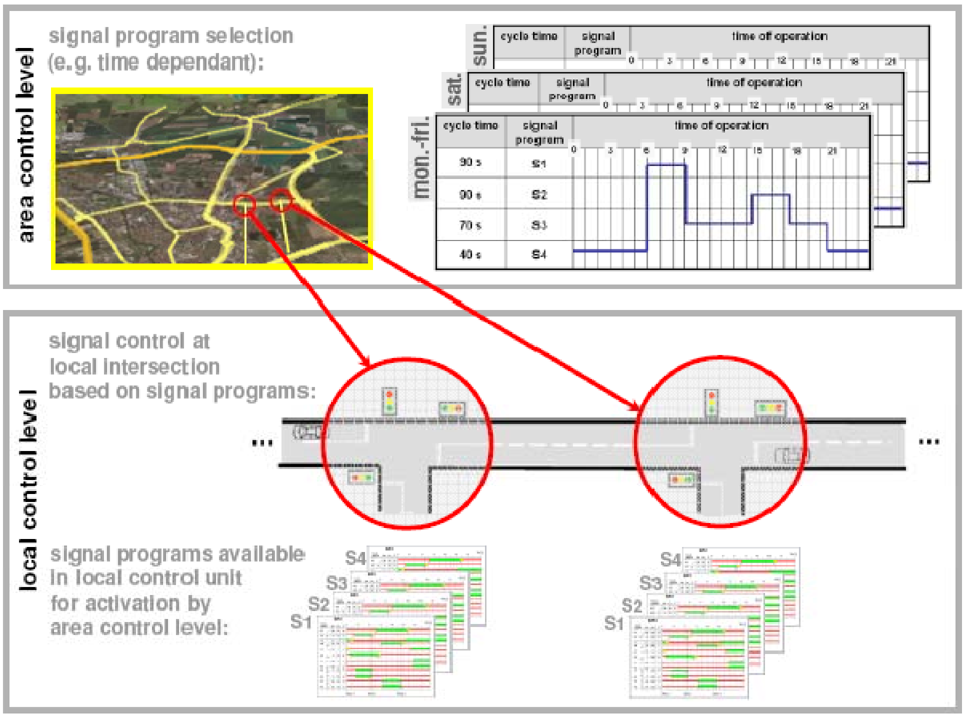


Figure 4. Interrelation between area and local control level
Source: Vesper (2009)

With the selection and activation of signal programs, it is possible to adapt signal control of signalized intersection at local control level to different traffic situations during the day. In time periods with medium or low traffic volumes it is e.g. possible to activate signal programs with a shorter cycle time than in peak hours, because the required amount of green time is lower.

As introduced in Table 1, a time-dependent or a traffic-dependent selection and activation of signal programs can be applied on area control level.

In case of time-dependent selection, the 24-hours of operation will be subdivided in fixed time periods. During the fixed time periods specific signal programs will be selected on the area control level and be activated by giving an instruction to the local control level. For this reason, different signal programs will be provided in the controller units of traffic signals on the local control level. In Figure 4 the interrelation between area and local control level is shown as an example for a time-dependent selection of signal programs.

In case of traffic-dependent selection, the 24-hours of operation will also be subdivided in different time periods. But the start and end of time periods will be defined by the traffic volumes measured in the road network. If the measured traffic volumes at selected reference points are within a pre-defined range, the area control level gives the instruction to switch from one signal program to another. Respectively the signal program will be activated on the local control level.

In German medium sized cities (100-300 thousand inhabitants) the following shares of signalized intersections are controlled by area control level (cf. Moerner et al., 2008):

- 48 % of signalized intersections by time-dependent selection,
- 18 % of signalized intersections by traffic-dependent selection,
- 34% of signalized intersections are not controlled by area control level.

In some Thai cities, especially at higher ranking roads of road network traffic control at signalized intersections is controlled by area control level. Here mostly the time-dependent selection is applied. But in most of the Thai cities area control level is not applied at all. In these cities road traffic safety as well as quality of traffic flow could be improved significantly by implementation of area control level. For this reason the application of area control level should be recommended as a regular solution in the planned Thai design guideline for the design of traffic control at signalized intersections.

5.2 Local control level

Control decisions on the local control level are decisive for road users at a local intersection. The control instructions are stored in signal programs which are normally implemented in the controller unit of the local traffic signal.

It is recommended that several signal programs should be provided in controller units on the local control level. In this way, different signal programs can be activated during the 24-hours of operation. Depending on the traffic situation in the road network, one can provide different signal programs for working-days (Monday to Friday) and the two weekend-days (Saturday and Sunday) as follows:

- morning-peak-hour program (mp),
- afternoon-peak-hour program (ap),
- day-program (dp),
- night-program (np).

Different types of signal control can be applied on the local control level. According to the variability of signal programs, one can distinguish between the following types of signal control:

- pre-timed,
- semi-actuated,
- fully-actuated.

The classification to one of the types can be conducted on the basis of the variability of elements in the signal program as shown in Table 2.

In Germany additionally the “main-direction-permanent-green” (FGSV, 1992) is a frequently used special case of fully actuated signal control. In this special type of signal control the signals of the main directions at signalized intersection show permanent GREEN and the road users coming from the minor directions receive GREEN only on request.

Table 2. Types of signal control used on local control level in Germany
Source: Vesper (2009) according to FGSV (1992)

Types of signal control		Variability with the view on different elements of signal program							
General term	**Main characteristic**	**length of green time**		**Phase sequence**		**Number of phases**		**Length of cycle time**	
		fixed	variable	fixed	variable	fixed	variable	fixed	variable
Pre-timed	Fixed signal program	X		X		X		X	
Semi-actuated	Adaption of green time		X	X		X		X	
	Swapping of phases	X			X	X		X	
	Insertation of demand phases		X		X		X	X	
Fully-actuated	Free variability of signal program		X		X		X		X

In Asian countries like in Thailand, manual traffic control is applied especially during peak hours on higher ranking roads of the road network. In this case traffic control is realised by traffic police and it substitutes temporarily traffic control by signal programs.

Pros and cons of pre-timed signal programs:

Traffic control by pre-timed signal program is connected with several pros and cons. Main pros of pre-timed signal control compared to semi-actuated or fully-actuated control are:

- the structure of the signal program is relatively simple,
- the signal program can be easily adapted to changing traffic conditions in the road network,
- construction, operation and maintenance costs of traffic signals are lower due to simple signal programs and simple technical equipment (no detectors, loops and other sensors …),
- the co-ordination of traffic signals is normally based on a fixed signal program
- structure, similar to pre-timed control. Accordingly, actuated signal control is more or less not suitable for use in co-ordinated road sections or road networks. Especially fully-actuated signal control should not be applied in case of coordinated intersections (cf. Brilon et al., 2007; Gartner et al., 1995),
- in practise detectors of actuated controlled traffic signals, like e.g. radar sensors or loops are often not in operation because of technical defects for several reasons (like e.g. maintenance problems). In this case actuated signal control functions similar to pre-timed signal control, as signal control will not adapt to changing traffic volumes.

Main cons of pre-timed signal control are:

- in case of low capacity utilization, actuated signal control can assign available green time more efficiently to the different traffic streams than pre-timed control,
- giving priority to selected road user groups (like e.g. public transport) at signalized intersections is not possible with pre-timed control.

In German medium sized cities (100-300 thousand inhabitants) the following types of signal control are implemented in traffic signals on local control level (cf. Moerner et al., 2008):

- 12 % pre-timed signal programs,
- 48 % semi-actuated signal programs,
- 34% main-direction-permanent-green,
- 6 % fully-actuated signal programs.

In Thai cities mostly pre-timed signal programs (nearly 100%) are used for signal control on local control level. In some cities, like e.g. Bangkok, Chiang Mai and Pattaya, actuated signal programs are installed, but often these systems are only partly or not in operation because of defect loops and sensors and function like pre-timed controlled intersections (cf. Ponlathep, 2009).

Figure 5. Manual traffic control on local control level by traffic police in Bangkok
Source: Vesper (2009)

Furthermore especially at higher ranking intersections traffic lights are often manually controlled by traffic police during peak hours. Here police officers give the available green time to the traffic streams which want to cross the signalized intersection directly from their control-booth near the intersection as shown in Figure 5.

In emerging countries like Thailand the application of pre-timed signal control should be recommended as the standard solution for traffic control on local control level, because of the related low costs for realization, the simplicity, the efficiency and further pros as mentioned before. But it is also recommended that several pre-timed signal programs should be provided on the local control level which can be activated by the area control level in a time or traffic dependent way.

6. USER GROUPS

Different road user groups, like motorised vehicles (4-wheelers, 2-wheelers), public transport, cyclists and pedestrians use road infrastructure. Therefore the needs and requirements of all road user groups should be considered in the design of signalized intersections.

In European countries normally all road user groups are considered in the design of signalized intersections. This means that also vulnerable road users like e.g. pedestrians are considered in signalization at signalized intersections as well as at separated signalized pedestrian crossings.

In Thailand, normally only motorised road users are considered in the design of signalized intersections. Pedestrians or bicyclists are mostly not considered, with exceptions at some signalized intersections e.g. in Bangkok or in Chiang Mai.

Figure 6. Signalized intersection without consideration of pedestrians in the design of signalized intersections
Source: Vesper (2009)

In the future all road user groups should be considered in the design of signalized intersections in Thailand. In this way it is possible to improve road traffic safety especially for vulnerable road users which are often involved in serious accidents.

7. PHASING

The number of phases and especially the guidance of turning movements at signalized intersections have a great influence on road traffic safety.

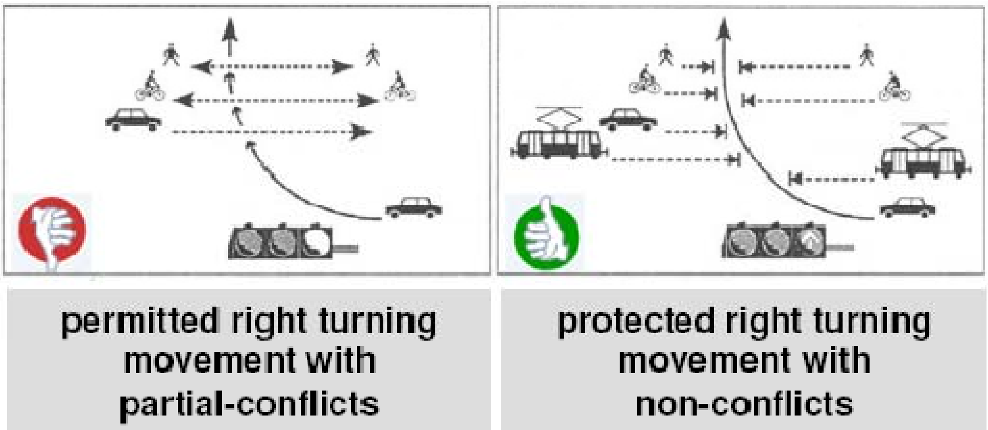


Figure 7. Right turning vehicle without conflicts (A) and with partial conflicts (B)
Source: According to Borsos and Koren (2008)

In Germany, Hungary as well as in Thailand signal programs with 2, 3 or 4 phases are in use.
In general one can guide right1) turning vehicles as a protected movement or a permitted movement at signalized intersections. The advantage of the protected guidance of right1) turning vehicles is that vehicles can cross the intersection in a separate phase without giving priority to other prioritized traffic streams like opposing thru or left2) movements.

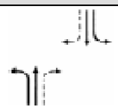
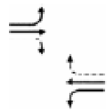
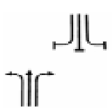
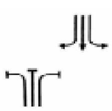
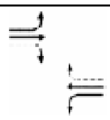
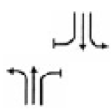
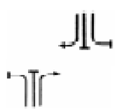
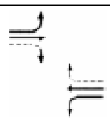
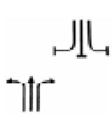
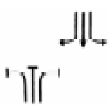
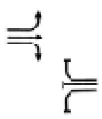
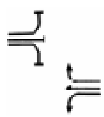
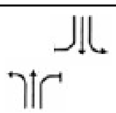
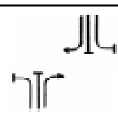
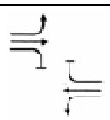
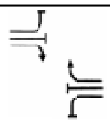
In case of a permitted guidance right1) turning vehicles have to give the priority to opposing thru and left2) movements at the intersection (see Figure 7, B).

Accident investigations in Germany show that the guidance of turning movements at signalized intersections has a significant influence on road traffic safety as shown in Figure 2.

In case of protected turning movements (3 or more phases) at signalized intersections, the accident cost rates (ACR) are significantly lower than in case of permitted turning movements (2 phases).

In Table 3 different phase systems and the related estimated impact on road traffic safety are shown exemplarily for an X-junction.

Table 3. Phase systems and the estimated impact on road traffic safety
Source: Vesper (2009)

number of phases	phase sequence				estimated impact on road traffic safety
	1 -main road-	2 -main road-	3 -secondary road-	4 -secondary road-	
2 phases					
3 phases					
3 phases					
4 phases					
4 phases					

Based on experiences made in Germany (cf. Figure 2) and further countries the protected guidance of right1) turning movements (3 or more phases) should also be recommended for signal control at signalized intersections in Thailand as regular solution.

1) In case of right hand driving (e.g. Germany or Hungary) please substitute right by left.
2) In case of right hand driving (e.g. Germany or Hungary) please substitute left by right.

8. SIGNAL PROGRAM PARAMETERS

The main parameters in the design of signal programs are amongst others the GREEN-time, AMBER-time, RED-time, inter-green-time and the cycle time.

In the following two sub-chapters the cycle time and the inter-green-time are discussed with the view on road traffic safety and quality of traffic flow in detail. Based on a comparison between Germany and Thailand, some recommendations and hints are given.

8.1 Cycle time

The cycle time (t_C) also known as cycle length is the time in seconds required for one complete colour sequence of signal indication at signalized intersections.

In Germany and Thailand different ranges of values are recommended or applied for cycle times as shown in Table 4.

The standard cycle times in Thailand are significantly higher than the respective values in Germany.

Table 4. Comparison of cycle times applied in Germany and Thailand
Source: FGSV (1992); Taneerananon et al. (2008)

Cycle time (t_c) –kind of value-	Germany (s)	Thailand (s)
minimum	30	---
standard	50-75	T-junction: 120*)-180*)
maximum	90(120) **)	---
in practice		in some cases up to 400
	*) limiting value which is applied but not regulated by guidelines or recommendations **) value in brackets only in exceptional cases	

In general the choice of cycle time has a significant influence on the “quality of traffic flow” as well as on “road traffic safety”. Here one has to consider that partly the influence on the mentioned aspects can be conflicting. With the view on “traffic flow” long cycle times are applied to gain high capacities at signalized intersections. But often long cycle times are also connected with longer delay in approaches of intersections or are partly not applicable in case of coordinated intersections.

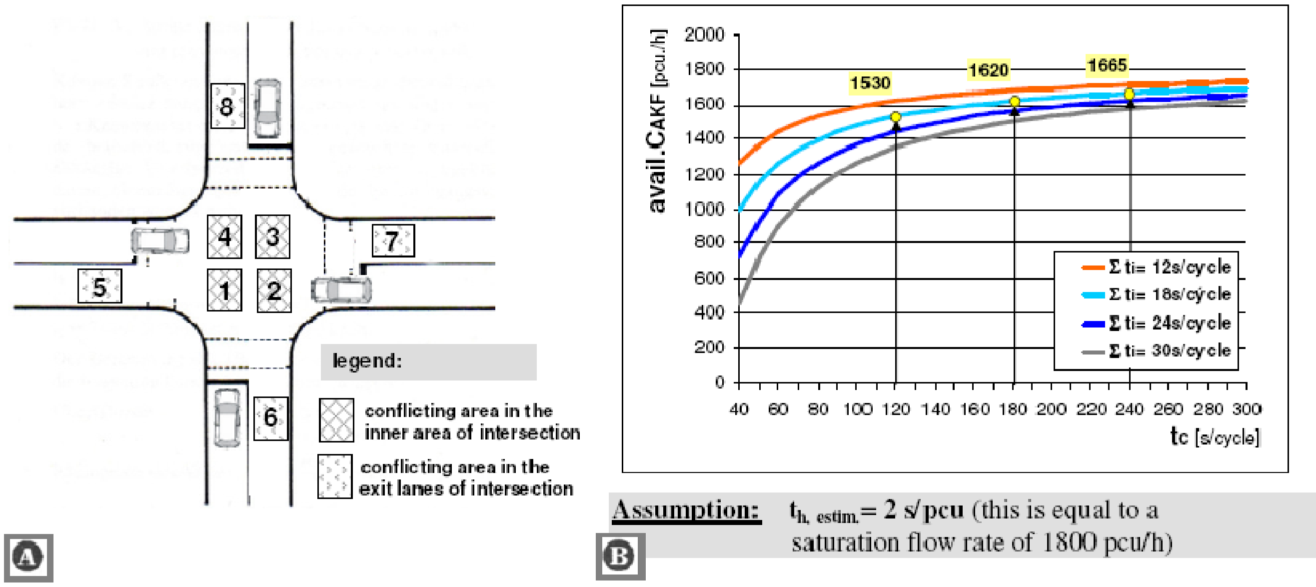


Figure 8. Conflicting areas at an X-junction (example, A) and interrelation between capacity of conflicting area and cycle time (B) Source: Vesper (2009) and Vesper et al. (2008)

The capacity of conflicting areas (C_{AKF}) at signalized intersections can be calculated by a predimensioning method called "AKF-Verfahren" according to Mueller (1969). This method is similar to the well known "Critical Movement Summation" method which is applied in many parts of the world.

The capacity of conflicting areas (C_{AKF}; see Equation 1), hereafter named as capacity, describes the available capacity on different conflicting areas at a signalized intersection. In general one can distinguish between conflicting areas in the inner area of the intersection and conflicting areas in the departure area of the intersection as shown in Figure 8 for a Xjunction.

The interrelation between cycle time (t_C) and capacity (C_{AKF}) of signalized intersections is shown in Figure 8 for different total intergreen times. The diagram makes obvious that in case of low cycle times (up to ~70 seconds) the increase of cycle time has a big influence on the capacity of intersection. In contrast, higher times have an increasingly smaller influence on capacity e.g. in a range over ~120 seconds. In Table 5 the interrelation of cycle times and capacity is explained in a descriptive example. Here the figures clearly show that the increase of cycle time from 120 s (index=100%) to 240 s (200%) has only a small influence on capacity. The doubled cycle time lead only to an increase of capacity by 6 to 17% according to the respective total intergreen time.

$$C_{AKF}=\frac{3600-\frac{3600}{t_c}*\sum t_{i,estim.}}{t_{h,estim.}} \qquad (1)$$

C_{AKF}: capacity of conflicting area, [veh/h]
t_c : cycle time, [s/cycle]
$\sum t_{i,estim.}$: total estimated integreen time per cycle at an intersection[s/cycle]
$t_{h,estim.}$: estimated time headway, [s/pcu]

Table 5. Interrelation between cycle time (t_i) and capacity of conflicting area (C_{AKF})
Source: Vesper (2008)

Cycle time	Capacity of conflicting area (C_{AKF}[veh/h]) subject to different total intergreen times ($\sum t_i$ [s/cycle])			
t_c[s]	$\sum t_i$=12s	$\sum t_i$=18s	$\sum t_i$=24s	$\sum t_i$=30s
120 (index=100%)	1620 (index=100%)	1530 (index=100%)	1440 (index=100%)	1350 (index=100%)
180 (index=150%)	1680 (index=104%)	1620 (index=106%)	1560 (index=108%)	1500 (index=111%)
240 (index=200%)	1710 (index=106%)	1665 (index=109%)	1620 (index=113%)	1575 (index=117%)

As indicated above, long cycle times can also have a negative impact on "quality of traffic flow". For instance in case of undersaturated conditions, long cycle times ($t_C > t_{C,opt.}$; $t_{C,opt}$ = delay optimised cycle time e.g. according to Webster, 1958) are often directly connected with relatively longer delay and longer queues especially in uncoordinated approaches of signalized intersections.

Furthermore, in case of long cycle times like for instance in the range of ~120 seconds or above, it becomes more and more difficult to coordinate consecutively located intersections in existing road networks. Due to long cycle times the width of the green band becomes too wide as well as the distance between "green band intersection points" becomes too long to design a functioning "green wave" in both directions. As a consequence, one has often to serve the traffic in one direction in an uncoordinated way which is normally directly connected with a lower "quality of traffic flow".

Additionally, long cycle times can also have a significant negative influence on "road traffic safety". In general road users want to cross an intersection as soon as possible. If RED-time at intersections is too long and road users need to wait a long time for their GREEN-time, they are more and more likely to cross the intersection during the RED-time. If road users ignore traffic signals and cross the intersection in unprotected time periods, dangerous situations will happen more often which could lead to traffic accidents. For this reason, upper boundary values of RED-times are defined in German guidelines. According to FGSV (1992) the maximum RED-time should not exceed 60 seconds for pedestrians and bicyclists and 120 seconds for vehicle traffic. In comparison to Germany, in Thailand no maximum values are in application for maximum RED-times. The introduction of comparable maximum values of cycle times in Thailand could contribute to the objective of improving road traffic safety at signalized intersections in the future.

8.2 Intergreen Times

According to German guidelines FGSV (1992), the intergreen time is defined as the time interval between the end of the green time for one traffic stream (respectively signal group) and the beginning of the green time for the next, crossing or entering traffic stream (respectively signal group). Although the same definition of "intergreen time" is used in Germany and Thailand, the way of calculation is totally different in the two countries as shown in Table 6.

Table 6. Calculation methods of intergreen time
Source: FGSV (1992); Ponlathep (2009)

Country	Calculation method	Legend	No.
Germany	$t_i = t_{cr}+t_{cl}-t_e$ $t_i = t_{cr}+\frac{s_0+l_{veh}}{v_c}+\frac{s_e}{v_e}$	t_i : intergreen time [s] t_{cr}: crossing time [s] t_{cl}: clearance time [s] t_e : entering time [s] s_0: distance from stop line to conflict point of clearing traffic stream [m] l_{iveh}: length of clearing vehicle [m] v_c: speed of clearing vehicle [m/s] s_e: distance from stop line to conflict point of entering traffic stream [m] v_e: speed of entering vehicle [m/s]	(2)
Thailand	Two fixed values: t_i = 3 or 5 s	t_i : intergreen time [s]	(3)

In Germany the intergreen time is calculated by a formula as shown in Table 6. Here the intergreen time can be subdivided in the following parts:

- the crossing time (t_{cr}),
- the clearance time (t_{cl})
- and additionally the entering time (t_e).

In Thailand no calculation method is in use to calculate intergreen times. Only fixed values of 3 and 5 seconds are applied as intergreen times. In case of compact intersections 3s and in case of large intersections 5s are applied. A case study executed by Taneerananon in Thailand showed that the application of fixed intergreen times led to very heavy accidents at investigated intersections because the required intergreen times were often significantly higher than the applied values.

The implementation of a calculation method in Thailand similar to the German method could be an effective measure to counteract the current problems in intergreen time calculation in Thailand. But it is necessary to adapt the German formula (see Equation 2) to Thai conditions.

9. FIELD STUDIES IN THAILAND FOR PREPARATION OF GUIDELINES

A main aspect in the preparation process of the planned guidelines for the “Design of Traffic Control at Signalized Intersections” is the adaptation of design methods and parameters to national Thai conditions as described in Vesper et al. (2010).

The adaptation can be realized by field studies which need to be conducted in Thailand. In this way it is possible to consider behaviour of Thai road users and further specific Thai aspects in proposed design methods and parameters of planned new design guideline for the design of traffic control at signalized intersections.

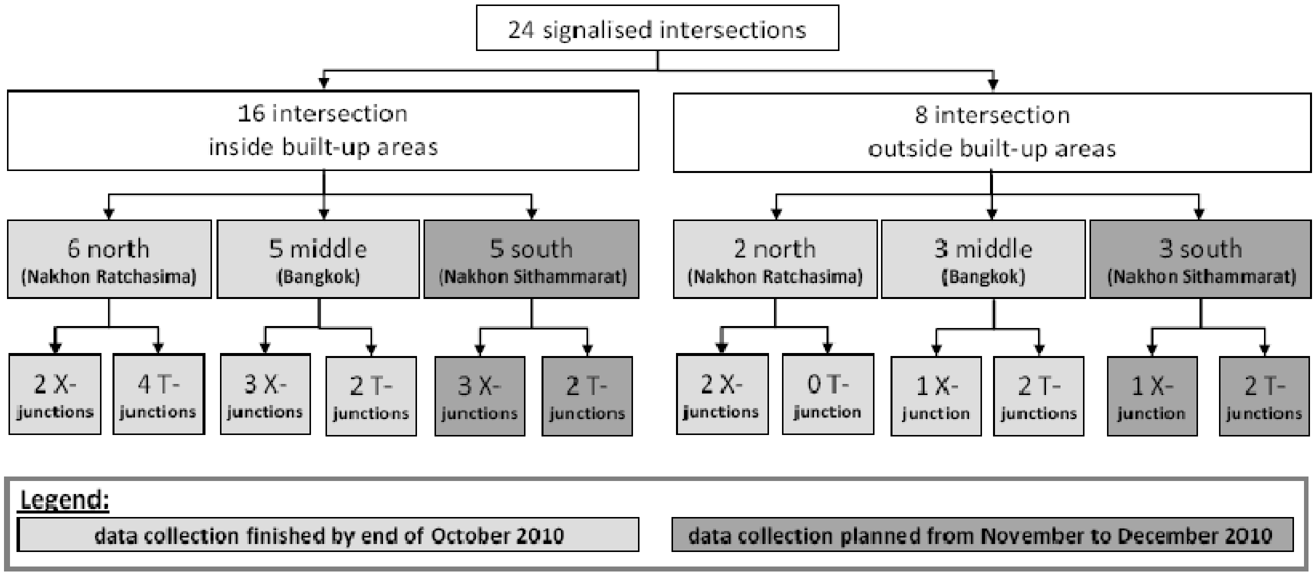


Figure 9. Scale of planned field studies at signalized intersections for adaptation of design methods and parameters to national conditions in Thailand
Source: Blei (2009)

It is planned that required data for adaptation of design methods and parameters in the design of traffic control at signalized intersections will be collected by conduction of comprehensive field studies at signalized intersections in Thailand as shown in Figure 9. Altogether 24 signalized intersections will be investigated inside as well as outside built-up areas in Bangkok, Nakhon Ratchasima and Nakhon Sithammarat.

Based on the results of field studies it is possible to consider different specific aspects of road traffic at signalized intersection in Thailand in upcoming methods of planned design guideline like e.g.:

- left hand driving,
- traffic rules and traffic signs,
- requirements of road user groups at signalized intersections,
- modal split,
- driven speeds,
- capacity,
- driving behaviour,
- acceptance of traffic signals.

Additionally it is possible to identify current deficits in the design of traffic control at signalized intersection which can be addressed in the planned guideline afterwards.

10. CONCLUSION

Traffic control by traffic signals is successfully applied to control traffic flow at signalized intersections in road networks. Normally signal control at signalized intersections is realized in European countries and in Thailand in a similar way. But in some cases there are essential differences which have often a negative impact on road traffic safety - especially in the design of signal programs on local control level.

The network partners of “NICE on RoadS” are preparing a guideline for the “Design of Traffic Control at Signalized Intersections” for Thailand, on basis of the “Methodology for Design Guideline Implementation in Thailand - Based on International Technology and Knowledge Transfer” (cf. Vesper et al., 2010). In the design guideline up-to-date methods of signal control will be described in detail. Existing lacks of knowledge will be closed like e.g. by an introduction of a calculation method for intergreen times or by the introduction of limiting values for cycle times for Thailand.

Furthermore the use of signal programs with 3 or more phases with protected guidance of right turning vehicles will be promoted because of the strong influence on road traffic safety. Beside the highlighted methods and parameters, also several other methods and parameters will be adapted to Thai conditions too.

In the future, the upcoming design guideline will provide road engineers, road designers and other target groups in the design traffic control at signalized intersections necessary and useful knowledge, how to design efficient and safe signal control at signalized intersections in Thailand.

The authors are sure that the guideline will contribute to the worldwide challenge of improving road traffic safety – especially in Thailand.

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TRAFFIC SIGN EXPERIMENT UPSTREAM OF CURVES ON TWO-LANE HIGHWAYS

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Abstract: This research presents an experiment of various traffic sign installations upstream of curves on two-lane highways. In Thailand, the design and installation of traffic signs at curves are strictly followed international standards with insufficient actual field test; therefore, some detailed designs and/or specification might not suit Thai drivers' behaviors well. Additionally, most Thailand's rural areas are only accessible by a two-lane highway with substandard and unsafe design due to a limited right-of-way. Appropriate signage is a simple and economical way for accident prevention at this roadway type. To understand drivers' behaviors due to traffic signs, five different traffic sign configurations were set up upstream of curvatures. Then, driving speeds were recorded by speed guns and statistically analyzed. The results show that only one warning sign is appropriated to install at large-radius simple horizontal and regular vertical curves. Nevertheless, a warning sign with speed limit and "Dangerous Curve" message sign should be installed together at small-radius simple and small-radius/large-radius reverse curves. In conclusion, the experiment shows that different signage configurations are appropriate with different types of roadway curvatures.

Key Words: Traffic Signs, Highway Design, Driving Behavior, Traffic Engineering

1. INTRODUCTON

Currently, the design and installation of traffic signs in Thailand are abided by international standards with few of field experiments to understand Thai drivers' behaviors. In addition, Thailand's rural areas are mostly accessible by two-lane highway system with substandard and unsafe design due to insufficient and limited right-of-way. Any geometric improvement at these existing highways is costly and sometimes impossible to do. Design of appropriate signage corresponding to drivers' behaviors is probably one of simple and economical ways for accident prevention at this roadway type. Therefore, the experiment presented herein is to examine drivers' behaviors due to various traffic signs upstream of curves on two-lane highways. Understanding of how drivers react to different signage configurations would lead to proper design of this type in the future.

The remainder of the paper is organized as follows. Section 2 summarizes related background research as well as current standards. The study site and design of experiment are described in Section 3. Section 4 presents the data from the experiment. Section 5 summarizes the evaluation according to different performance indices. Then, the sixth and final section contains concluding remarks as well as areas of further research.

2. LITERATURE REVIEWS

This section combines two different literatures regarding this research. The first subsection is the reviews of Thai and U.S. standards in design and install of traffic signage. Secondly, previous studies of driving behaviors approaching two-land roadway curvatures and signage experiments are discussed.

2.1 SIGNAGE DESIGN GUIDELINES

In the U.S., FHWA (2003), or the Manual on Uniform Traffic Control Devices (MUTCD) is the current general standard of designing and installing traffic signs. It is notable that the earlier version of MUTCD was used as an international standard. Later, Thailand's organizations adapted this standard into their ones. It was found that several organizations in Thailand issued signage design guidelines, e.g., the Department of Highways (DOH), the Office of Transport and Traffic Policy and Planning (OTP), etc. First, DOH (1988) has been used as a handbook of designing and installing traffic signs for all types of highways within DOH's responsibility. Later, OTP (2004) was issued as the manual of Application for Traffic Control Devices at curve areas. This has been a standard of designing and installing traffic signs for all other roadway-related agencies in Thailand. Unsurprisingly, these manuals are different. The comparisons among these manuals for signs upstream of curves are shown in Table 1 below.

Table 1. Comparisons of Signage Design Manuals

Manual	DOH (1988)	OTP (2004)	FHWA (2003)
Regulatory Sign Shape	Circle	Circle	Rectangle
Warning Sign Shape	Rectangle (Warning Sign)		
Lateral Locations of Signs (from the edge of the traveled way)	4.00 m.	3.60 m.	1.80 m.
Height of Signs	1.20 m. from the edge of the traveled way		
Conditions for Warning Sign Placement	No condition	3 conditions	2 conditions

2.2 DRIVING BEHAVIORS ON ROAD CURVES AND PREVIOUS EXPERIMENTS

From literature review, it was found that study of driving behaviors on road curves have not been thoroughly conducted by field experiments before. Examples of previous studies are as follows:

Milosevic and Milic (1990) studies drivers' perception of their driving speed on curves by assigning 206 drivers to estimate their vehicle speeds in the central part of a sharp smallradius curve and compare their estimated speed given by drivers after passing the curve with their actual ones at the central point of the curve. It shows that drivers usually underestimated their vehicle speeds. Speed estimation was more accurate for drivers who noticed warning and speed limit signs. Additionally, experienced and middle-aged drivers reported more accurate estimates than younger, less experienced ones.

In Thailand, similar observations were conducted. Yongboot, *et. al.* (2006) studies drivers' behaviors on road curves by collecting accident data and physical route information from the DOH and collecting driving behavior data in the field. It shows that the speed reduction at small-radius curves is greater than one at large-radius curves. In addition, regular passenger cars exhibit highest speeds among all. It also shows that rented cars usually run faster than private cars on large-radius curves but similar on small-radius curves. However, this study did not vary signage configuration to test how drivers react to them at all.

Houten and Houten (1987) studies whether a "BEGIN SLOWING HERE" message sign can reduce speeds. The study site is in an urban area with lane-reduction from 4 to 2 lanes and the speed limit is reduced from 80 to 50 km/hr. It indicates that the message sign significantly produced reductions in the percentages of motorists travelling over the speed limit sign.

Vest, *et al.* (2005) studies the use of several warning signs and warning methods to identify factors affecting the reduction of vehicle speeds when traversing a horizontal curve. Three sites were selected from a list of proposed sites for the testing of various warning methods. Each warning treatment was installed and a five-day waiting period was allowed before operating speeds for the treatments were measured. The results found that the most effective of these treatments were the transverse lines, the new combination Horizontal Alignment/Advisory Speed Sign, and flashing lights on both the existing warning sign and new combination warning sign.

Bertini, *et al.* (2006) investigates the use of a dynamic curve warning system deployed at one site on northbound and southbound Interstate 5 in Myrtle Creek, Oregon, U.S. The system displayed directed messages on two dynamic message signs to drivers based on the detected speed of approaching vehicles. Speed samples were taken of vehicles with a laser ranging and detection device, recording both speed and distance information over seven days-four in the before period and three in the after period. The quantitative evaluation indicated that the advanced curve warning system was effective in reducing the mean speeds of passenger cars and trucks by approximately 3 mph for the southbound direction and 2 mph for the northbound direction. After the system was installed, the distribution of vehicle speeds was statistically different with a lower number of vehicles in the higher speed bins. Inception surveys of motorists at nearby rest areas revealed a positive perception of the system.

Comte and Jamson (2000) studies speed-reducing measures for curves which consisted of Variable Message Sign (VMS), in-car advice, speed limiter and transverse bars by using the University of Leeds Advanced Driving Simulator. It shows that speed limiters were the most effective measure; however, in terms of user acceptability this system was least preferred. Nevertheless, all other measures significantly reduced speeds when activated, in the order of approximately 6 km/hr. Although this enhance more understanding of drivers' behavior according to signage but the simulator could not fully represent actual driving situation.

Charlton (2006) researches the roles of attentive, perceptual, and lane placement factors in driver behavior at curves. Two groups of curve treatments were identified for testing with a driving simulator. The first group of treatments consisted of four combinations of warning signs designed to alert drivers to the presence of curves and to produce a reduction in curve approach speeds. The second group was comprised of several types of road markings designed to affect drivers' speed and lane position as they drove through curves. The results indicated that advance warning signs by themselves were not as effective at reducing speeds as when they were used in conjunction with chevron sight boards and/or repeater arrows. Of the road marking treatments, only rumble strips produced any appreciable reductions in speed and a herringbones road marking was found to produce significant improvements in drivers' lane positions.

According to the literature, to fully understand drivers' behaviors upstream of curves, a field experiment is necessary. This experiment must carefully be conducted in strategic locations and consist of varying signage configuration to measure vehicles' approaching speeds to the curves. The details of this experiment are shown in the following section.

3. STUDY SITE AND DESIGN OF EXPERIMENTS

This section presents the study site used in the experiments to study drivers' behaviors. This will be followed by experimental design by different signage configurations.

3.1 STUDY SITES

Five curves with distinct physical characteristics on two-lane highways were deliberately selected to perform an experiment. The sites must be two-lane highways with long distance upstream of curves to place and vary traffic signs. Also, traffic volumes on the road should be low to ensure free-flowing speeds of most vehicles. The drivers on routes should be mostly non-commuters to ensure unfamiliarity with the roadway with different signage configurations. Sides of roads should have some hidden places for observers to record vehicle speeds without being noticed by drivers. More importantly, the authority must allow the experiments.

At last, five curves along the Route No's 1003, 1008 and 5010 (within the responsibility of the Department of Rural Roads, Thailand) in Chon Buri as illustrated in Figure 1 fit the above criteria and were selected. These five curves have different physical characteristics as follows:

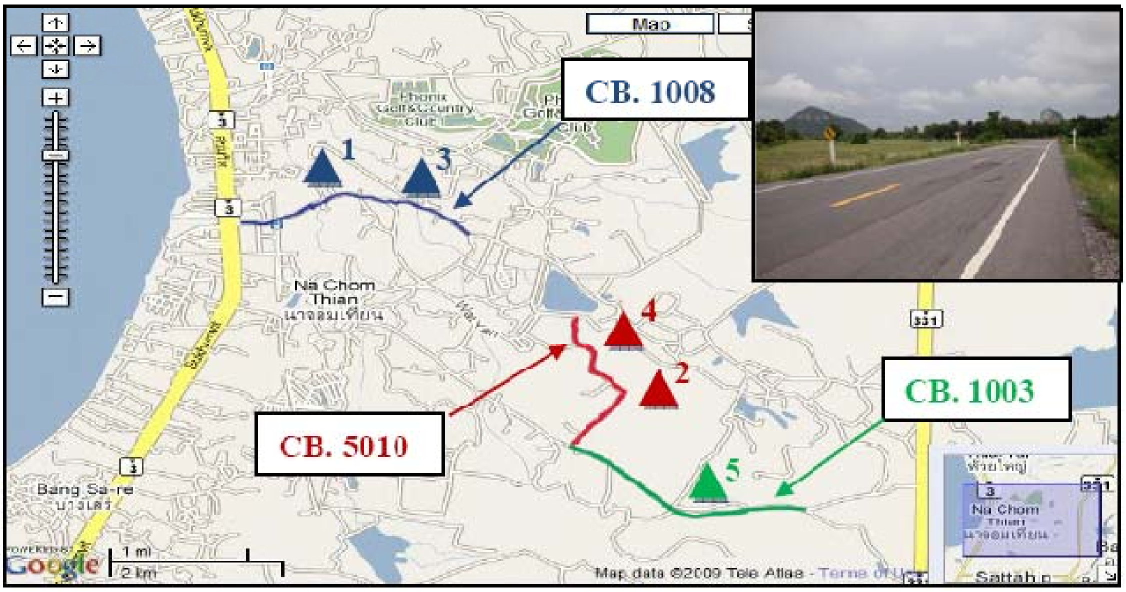

Figure 1. Study Sites in Rural Chon Buri, Thailand (Modified from Google Map)

Curve 1 is a large-radius (>100 meter) simple horizontal curve (LRSHC). The curve is selected on Route CB.1008 with about 110-meter curve radius. Both sides of the roads are small community.

Curve 2 is a small-radius (<100 meter) simple horizontal curve (SRSHC). The curve is selected on Route CB.5010 with 30-meter curve radius and 15-km/hr design speed. Sides of the roads are covered with groves and eucalyptus trees.

Curve 3 is a large-radius reverse horizontal curve (LRRHC). The curve is selected on Route CB.1008. It consists of two large (110-m)-radius simple horizontal curves with opposite center points of curves. Sides of the roads are covered with groves and eucalyptus trees.

Curve 4 is a small-radius reverse horizontal curve (SRRHC). The curve is selected on Route CB.5010. It consists of two small (20-m and 60-m)-radius simple horizontal curves with opposite center points of curves. Sides of the roads are covered with cassava plantation.

Curve 5 is a crest vertical curve (CVC) with less than 7%-slope. The curve is selected on Route CB.1003 with 3.5%-slope. Sides of the roads are covered with groves and trees.

3.2 DESIGN OF EXPERIMENT

To study how drivers react to different signage. Five traffic sign configurations were installed upstream of each curve. Signs in this experiment consist of warning, "Dangerous Curve" message and speed-limit signs. All signs are followed OTP (2004) unless stated otherwise.

Figure 2 presents five types of signage configurations. Only a warning sign is used in Configuration A at X_3, about 100-200 meter upstream of X_4, or the beginning of curvatures (P.C.) The dimension of the circle sign is 60-cm diameter. Later, a 60-cm diameter speed-limit sign is added in Configuration B. In C, a "Dangerous Curve (โค้งอันตราย)" message sign is also installed at X_2, 100-200 meter upstream of X_3. In D, all signs in C are installed on both sides of the road. Finally, Configuration E is the 25% enlargement of all signs in C.

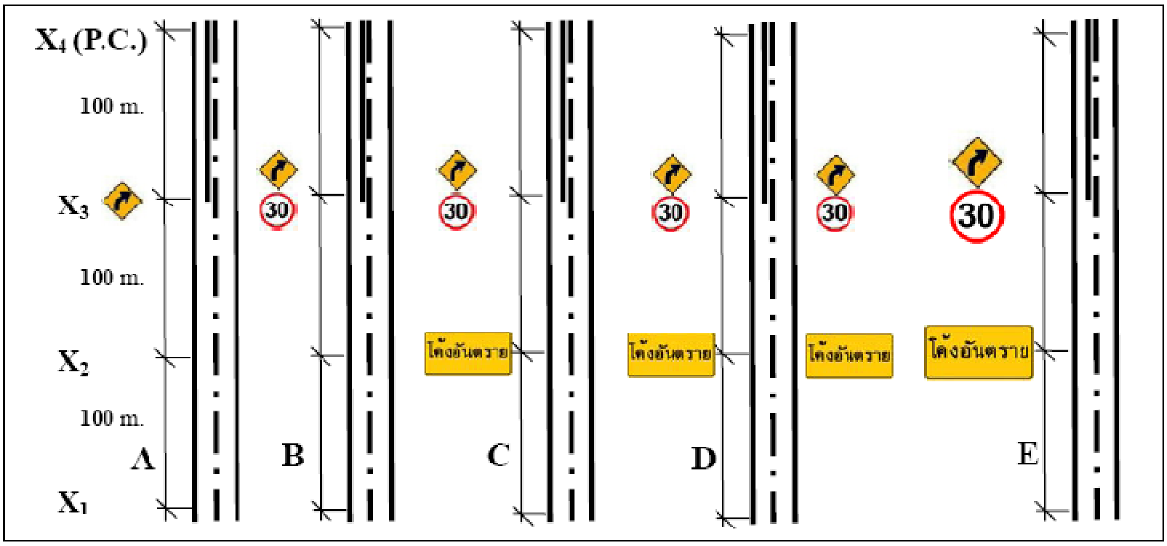

Figure 2. Traffic Sign Configurations in the Experiment

To collect speed data, four observers at X_1 to X_4 were hidden and used speed guns to collect vehicles' speeds passing them. In this study, only personal cars and pickups' speeds were collected. Also, the license plates of each vehicle were recorded to match them on each observation location as well as checking whether the vehicles are registered in Chon Buri province (or local vehicles), or elsewhere. For each configuration, 30-40 vehicle data were collected before changing to subsequent configurations. This was done on all five curves. Therefore, the whole data consists of 25 data sets or about 800 vehicles. The data are illustrated in the following section.

4. FIELD MEASUREMENT DATA

From the experiment, the mean speeds separated by each curve type, signage configuration, and license plate registration at the beginning of the curve (X_4) are shown in Table 2.

Table 2. Mean Speeds (km/hr) at the P.C. Classified by Registered Location

	Config. A		Config. B		Config. C		Config. D		Config. E	
Curve Type	**Local**	**Other**	**Local**	**Other**	**Local**	**Other**	**Local**	**Other**	**Local**	**Other**
1. LRSHC	36.5	35.2	54.33	58.0	52.7	51.4	55.3	53.9	55.2	58.0
2. SRSHC	50.7	48.6	52.7	49.8	48.6	45.2	50.0	47.3	42.5	45.6
3. LRRHC	50.0	55.3	53.0	50.4	47.9	50.4	48.0	47.3	51.7	48.2
4. SRRHC	43.5	40.1	41.1	39.2	37.6	39.9	36.7	37.2	38.5	40.2
5. CVC	61.9	66.7	60.3	64.5	67.3	63.7	71.4	66.7	65.7	62.3

Table 2 shows that there are no statistically significant differences between local and nonlocal vehicles. It is possible that the site study is a tourist place, far from central Chon Buri. Therefore, even vehicles registered in Chon Buri might not be familiar with the area and their drivers' behaviors are insignificantly different from out-of-area vehicles. Thus, the discussion below will treat all vehicles similarly and will show by each curve type in Figure 3.

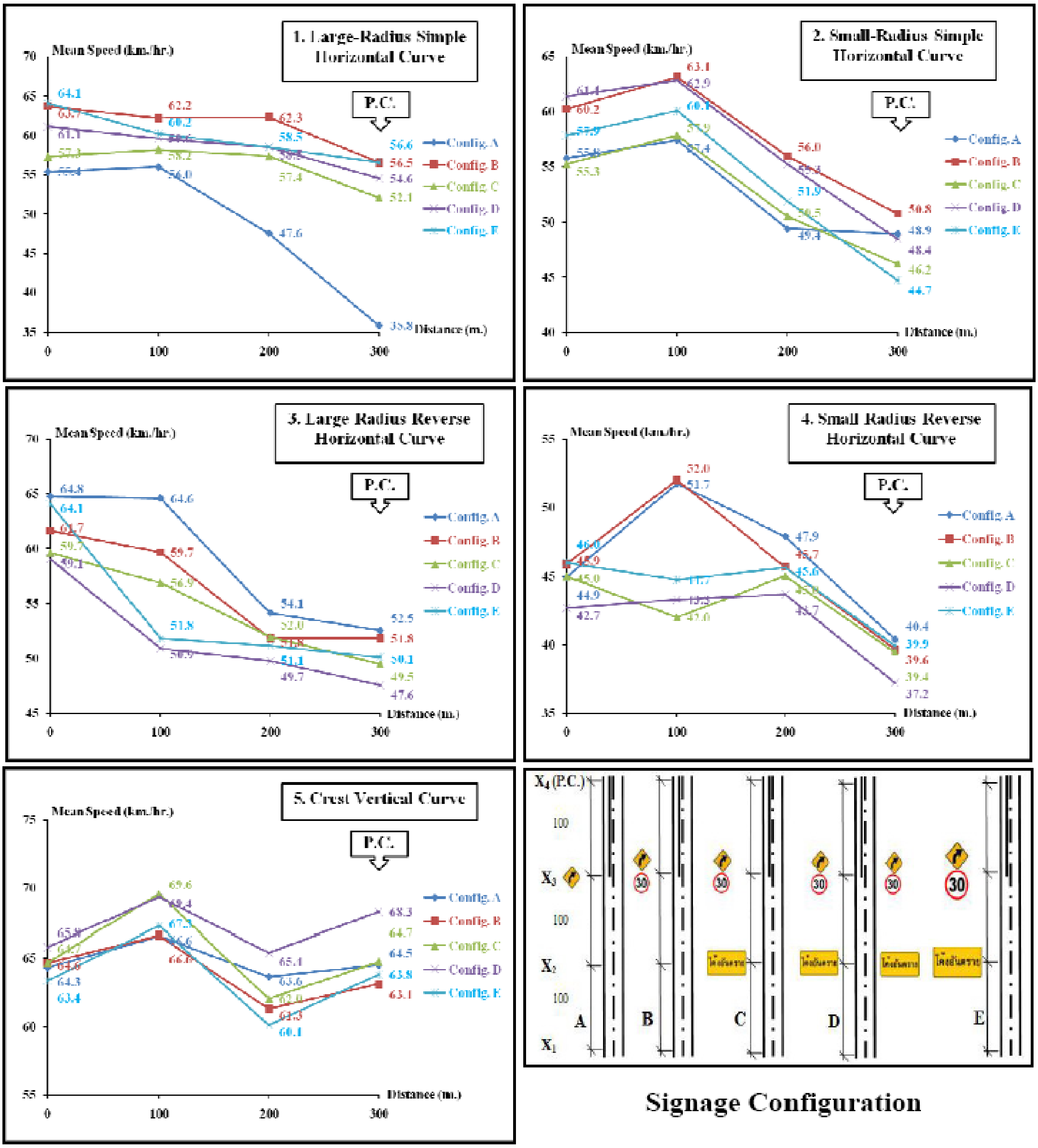

Figure 3. Mean Speeds at Each Location (Measured from X1) for Each Signage Configuration

Curve 1: LRSHC from Figure 3, the decreasing trend lines of mean speeds of all configurations except **A** are similar. The possible explanation is that **A** doesn't have a speed limit sign, so the drivers were more careful in speeding up since they didn't know how sharp the curve is. In addition, almost configuration, except **A** had mean speeds at the beginning point of the curve P.C. over 40 km/hr (speed limit).

Curve 2: SRSHC from Figure 3, the decreasing trend lines of mean speeds of **B**, **C**, **D**, and **E** are similar. The exception is A at the point just upstream of P.C. The explanation is that **A** doesn't have a speed limit sign, so the drivers did not slow down or overestimated the curve's speed limit. Also even with or without speed limit signs, all configurations have mean speeds at the P.C. over 30 km/hr (speed limit).

Curve 3: LRRHC from Figure 3, the decreasing trend lines of mean speeds of **A**, **B**, and **C** are similar. Nevertheless, **D** and **E** are different at the X_2 (200-m upstream of P.C.). It is possible that both sides of signs (**D**) and large signs (**E**) brought drivers' attention well, so they slowed down aggressively. At X_3, vehicles passing on signage configuration **A**, **B**, and **C** also slowed down rapidly since they were closer to the curve and saw the speed limit sign. However, all vehicles still passed the P.C. with mean speed more than the 40 km/hr (sign speed limit)

Curve 4: SRRHC from Figure 3, the decreasing trend lines of mean speeds of **C**, **D**, and **E** are different from **A** and **B** at X_2 (200-m upstream of P.C.). The explanation is that **A** and **B** don't have message signs, so the drivers did not slow down that far. Also, it was found that every configuration had mean speeds at the P.C. over 30 km/hr (sign speed limit).

Curve 5: CVC the effect of sign configurations on speed reduction at this vertical curve are almost none. Figure 3 shows that all trend lines are similar. They increases in the last 100-m upstream of the curve. It is possible that this curve is not too steep. Once the drivers had no sight restriction, they could speed up and disregarded the speed limit and warning signs. Therefore, every configuration had mean speeds at the P.C. over 30 km/hr (sign speed limit).

5. PERFORMANCE EVALUATION OF SIGNAGE CONFIGURATION

To find the most suitable traffic sign configuration, three key performance indices are established. They are 1) mean speeds at the P.C., 2) percentages of vehicles running below speed limit at the P.C., and 3) smoothness of speed reductions. Details and results for each index are as follows.

Mean speeds at the P.C.

Mean speeds of vehicles at the P.C. indicate overall effectiveness of configurations. Table 3 show mean speed data at the P.C. It was found that **A** brought the minimum mean speed (36 km/hr) to Curve 1 (LRSHC), **E** brought the minimum mean speed (45 km/hr) to Curve 2 (SRSHC), **D** gave the minimum mean speed (48 km./hr.) to Curve 3 (LRRHC), E gave the minimum mean speed (37 km/hr) to Curve 4 (SRRHC), and **B** gave the minimum mean speed (63 km/hr) to Curve 5 (CVC).

Table 3. Mean Speeds (km/hr) at the P.C. for Each Curve Type and Configuration

Curve Type	Config. A	Config. B	Config. C	Config. D	Config. E
1. LRSHC	**35.8**	56.5	52.0	54.5	56.6
2. SRSHC	48.9	50.7	46.1	48.4	**44.7**
3. LRRHC	52.5	51.8	49.4	**47.5**	50.1
4. SRRHC	40.3	39.6	39.4	**37.2**	39.9
5. CVC	64.4	**63.1**	64.7	68.2	63.7

Percentages of vehicles running below speed limit at the P.C.

For enforcement and safety purposes, the effectiveness of traffic sign configurations can be evaluated from the percentages of vehicles running below speed limit at the P.C. Table 4 shows that **A** gave the maximum percentage (71%) at the 40 km/hr limited speed to Curve 1 (LRSHC), **E** gave the maximum percentage (6%) at the 30 km/hr limited speed to Curve 2 (SRSHC), **D** gave the maximum percentage (16%) at the 40 km/hr limited speed to Curve 3 (LRRHC) and the maximum percentage (13%) at the 30 km/hr limited speed to Curve 4 (SRRHC). For Curve 5 (CVC), all vehicles drive passed the curve above signed speed limit regardless the configuration. This is evident that in all cases, drivers did not follow the speed limit signs.

Table 4. Percentages of Vehicles Running Below Speed Limit at the P.C

Curve Type	Config. A	Config. B	Config. C	Config. D	Config. E
1. LRSHC	**71%**	5%	10%	7%	8%
2. SRSHC	0%	0%	3%	3%	**6%**
3. LRRHC	4%	8%	12%	**16%**	12%
4. SRRHC	5%	0%	5%	**13%**	0%
5. CVC	0%	0%	0%	0%	0%

Smoothness of speed reductions

Any abrupt change in speed could cause traffic accidents (mostly from rear-end hit). Therefore, smoothness of speed reductions would be one of evaluation indicators. It is assumed that linearly reduction in driving speed from the free-flowing speed to the speed at the P.C. (the dotted line in Figure 4) would be ideal.

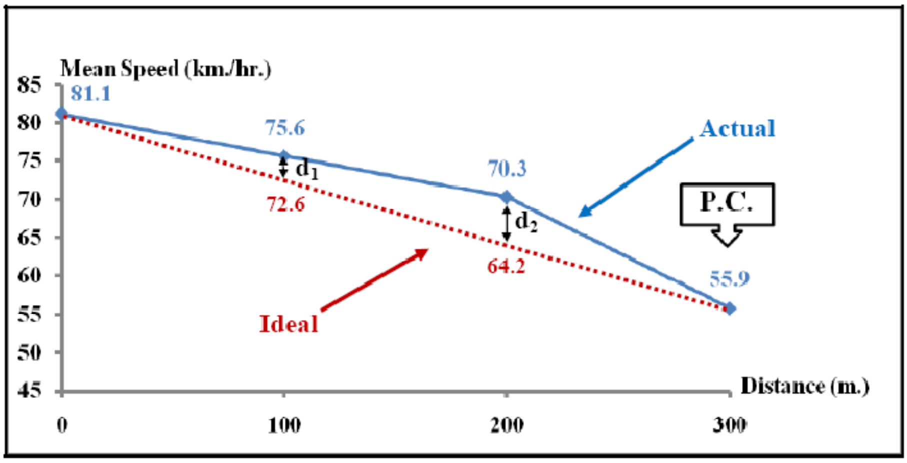

Figure 4. Ideal Speed Reductions Upstream of a Curve

The deviation from this ideal line can be calculated by establishing the unitless deviation (D) variable with following formulation:

$$D=\sqrt{\frac{\sum_{i=1}^{n}\left(\frac{d_i}{V_i}\right)^2}{n}} \qquad (1)$$

where d_i = Difference between an actual and ideal speed at measurement location *i*,

V_i = Ideal speed with constant deceleration at the position *i*, and

n = No. of measurements between the most upstream and the P.C. (= 2 in this case)

Table 5 shows the results of deviation (*D*) calculation for each curve and configuration. The minimum *D* (as close as zero) would indicate that the smoothness of speed reductions from the configuration is ideal. From Table 5, **E** gave the minimum *D* (0.01) to Curve 1 (LRSHC), **A** gave the minimum *D* (0.05) to Curve 2 (SRSHC), **C** gave the minimum *D* (0.01) to Curve 3 (LRRHC), **C** and **E** gave the minimum *D* (0.06) to Curve 4 (SRRHC), and **A** gave the minimum *D* (0.02) to Curve 5 (CVC).

Table 5. Deviation from Ideal Speed Reduction Line

Curve Type	Config. A	Config. B	Config. C	Config. D	Config. E
1. LRSHC	**0.14**	0.03	0.05	0.02	**0.01**
2. SRSHC	0.05	0.07	0.07	0.07	0.09
3. LRRHC	0.05	0.04	**0.01**	0.05	0.09
4. SRRHC	0.16	0.14	**0.06**	0.09	**0.06**
5. CVC	**0.02**	0.03	0.06	0.03	0.05

Note that these three distinct key performance indices alone might not determine the best configuration for each curve type. The other important factors are the ease in installation and modification from existing design practice. In addition, for the "Dangerous Curve" message sign in **C**, **D** and **E**, if excessively installed, drivers might not pay attention as expected.

Based on these factors, researchers finally conclude that **A** (one warning sign) is the most suitable for Curve 1 (LRSHC) and Curve 5 (CV), and **C** (a warning sign with speed limit below and a "Dangerous Curve" message sign) is the most suitable for Curve 2 (SRSHC), Curve 3 (LRRHC), and Curve 4 (SRRHC).

6. CONCLUDING REMARKS

In conclusion, the experiment shows that different signage configurations are appropriate with different types of roadway curvatures. The results suggest that only one warning sign is appropriated to install at large-radius simple horizontal and regular vertical curves. Nevertheless, a warning sign with speed limit and "Dangerous Curve" message sign should be installed together at small-radius simple and small-radius/large-radius reverse curves.

Key performance indices consisting of mean speeds at the P.C., percentages of vehicles operational indices to evaluate the results. However, other criteria such as costs, drivers' familiarity, ease in installation, etc. should incorporate with these indices and engineering judgment to determine appropriate signage configurations.

Due to field limitation, this research can be improved by collecting speed data at more measurement locations, choosing more curves with smaller-radii, higher free-flowing speeds and sharper speed reduction, choosing curves on urban highways. Also, to evaluate the real effectiveness in accident prevention, the research should compare accident rates and severity at the site before and after signage installation for a long period of time.

Future research is needed to test current and proposed traffic signs, including other traffic control devices such as pavement markings, guard rails, cat eyes, rumble strips, guide posts, etc. The research should be conducted at actual roadways to understand drivers' behaviors due to these devices and adjust them accordingly.

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ROUNDABOUTS – PREPARATION OF A DESIGN GUIDELINE FOR THAILAND

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Abstract: Roundabouts are usually very safe intersections. In some countries this type of intersection has a long history and a wide area of application, while in other countries they are relatively new and less frequently used. This paper contains a part of the results achieved in the Thai-EC project "Improving Road Traffic Safety in Thailand – A Common Challenge for European and Thai Universities" with financial support of the European Commission. One of the objectives of this project is to prepare and implement a guideline for the design of roundabouts in Thailand. The paper describes the main elements of the guideline in preparation, including the safety advantages of roundabouts, their preferred areas of application, the principles of their geometric design, along with some potential mistakes to be avoided. Results of the first on-site surveys at roundabouts in Thailand are shown which will be considered in the final version of the guideline.

Key Words: roundabout, guideline, traffic safety, NICE on RoadS, European Union

1. EXCERPTS FROM THE HISTORY OF ROUNDABOUTS

As it often happens, history can help us to understand today's problems. Wikipedia, the popular encyclopedia gives reasonable good definitions concerning the general term 'circular intersection' and the special terms 'rotary' and 'roundabout' (Wikipedia, 2009a, b, c).

The French architect Eugène Hénard was designing one-way circular intersections as early as 1877. … Other circular intersections were subsequently built in the United States; though many were large diameter 'rotaries' that enabled high speed merge and weave maneuvers. The experience with traffic circles and rotaries in the US was almost entirely negative, characterized by high accident rates and congestion problems. By the mid 1950s, construction of traffic circles and rotaries had ceased entirely. The experience with traffic circles in other countries was not much better until the development of the modern roundabout in the United Kingdom during the 1960s. (Wikipedia, 2009a)

A roundabout is one of several types of circular road junctions or intersections at which traffic is slowed down and enters a one-way stream around a central island. These junctions sometimes are called "modern" roundabouts, in order to emphasize the distinction from older circular junction types which had different design characteristics and rules of operation. The widespread use of roundabouts began when British engineers re-engineered circular intersections during the mid-1960s … to overcome its limitations of capacity and for safety issues. Unlike traffic circles, traffic approaching roundabouts is normally required to give priority to circulating and exiting traffic and to eliminate much of the driver confusion associated with traffic circles… (Wikipedia, 2009c)

Germany like other European countries has a long tradition of many decades regarding roundabouts. The roundabouts built between the 1930ies and the 1960ies were, however, limited in number and were mainly of a larger type with several lanes, both on the approaches and exits as well as on the circle. Over the years, these conventional roundabouts received a bad reputation regarding their safety. Thus, they were no longer built after the 60s and many of them were replaced by signalized intersections. (Brilon, 2005)

It was in the early 1980ies that experiments were made with new modern roundabouts inspired by the great success of roundabouts in the UK. At that time, single-lane compact roundabouts were of primary interest. The design standards from the UK, however, were not copied. Instead the basic principles of intersection design were applied quite consequently. These compact single-lane roundabouts became a story of great success. They are now a stateof- the-art solution as it is documented in the corresponding guideline. As a consequence, in recent years also other types of roundabouts receive more and more interest. Nowadays about 3000 to 5000 roundabouts are in operation in Germany (Brilon, 2005, 2008).

Hungary started with the modern roundabouts in 1990. During the last 20 years several hundred roundabouts were built either as new junctions or as the reconstruction of existing ones both in urban and rural areas. The design guidelines are being regularly updated; the current guidelines (HRS, 2001) will be replaced by a new version in early 2010.

Roundabouts are widely used also in the Netherlands. Dutch engineers have made a significant progress in finding new solutions of roundabouts solving special needs (Overkamp, Wijk, 2009).

Circular intersections have become an item of interest to the American transportation community after a fifty-year absence. (Waddell) A good overview of the theory and practice in various countries was given at the US National Roundabout Conference in 2008 (TRB, 2008).

2. AREAS OF APPLICATION AND ROUNDABOUT TYPES

A roundabout is a type of road junction where traffic streams circularly around a central island after first yielding to the circulating traffic. Thus there is no dedicated priority road at roundabouts. Every entering vehicle has to give priority.

It is important to emphasize, that junctions having a circular form but with different priority rules from the one above, cannot be considered as roundabouts.

Junction types have to be selected in the design process of road infrastructure according to the following general considerations:

- network,
- coherence to traffic volumes,
- traffic safety,
- capacity,
- environmental and other considerations.

The capacity of an intersection depends on the type of intersection as well as on the type of traffic control. The required capacity at an intersection is an important reason for selection of the intersection and traffic control type. In *Figure 1*, a qualitative estimation of the interrelation between capacity, type of intersection and traffic control is shown.

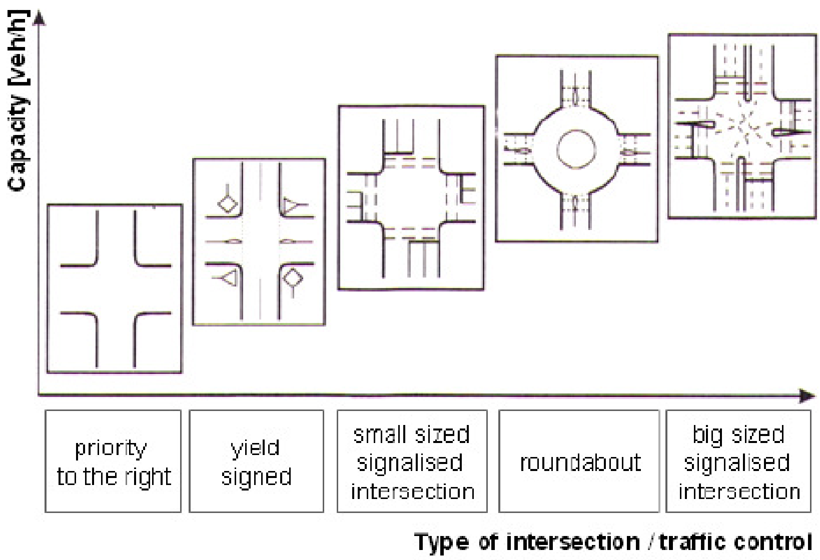

Figure 1. Capacity of different types of intersection and traffic control
Source: According to Schnabel and Lohse (1997)

Roundabouts are recommended for application both inside and outside built-up areas in order to achieve the following objectives:

- to improve road traffic safety at existing intersections which can be considered as blackspots due to
  - high speed level at the intersection,
  - sharp crossing angle of the intersection legs,
  - bad recognisability of the intersection,
  - bad visibility at the intersection,
- to reduce speed level at an intersection or at the entrance of a built-up area,
- to improve the capacity of an intersection,
- to avoid the maintenance and operation costs of traffic signals.

Roundabouts are especially recommended if

- the change in the priority of the crossing roads should be emphasised,
- there is a need to connect more than four intersection legs.

Application of roundabouts should be avoided if

- the traffic volumes in the entries differ too much (traffic volume on minor roads
- should be at least 15 % of major roads),
- the area available is not sufficient to build a roundabout following the requirements,
- the slope of outer circle would be above 4%.

In addition to its function as an intersection, a roundabout may be useful to

- facilitate a change in road category or road type, for example from dual carriageway to a single carriageway road;
- emphasize the transition from rural to urban environment (border of a built-up area);
- allow U-turns on roads whose cross section has a median and several private accesses.

The different types of roundabouts inside and outside built-up areas and their main characteristics are shown in *Figure 2*.

type of roundabout	mini	compact		large
		1-lane	2-lane	
application-area	inside built-up areas	inside/outside built-up areas	inside/outside built-up areas	inside/outside built-up areas
recommendation for application				
diameter (min-max)	13-22m	26-40m (inside) 30-50m (outside)	40-60m (inside) 45-60m (outside)	>40(60)m (inside) >50(60)m(outside)
diameter (recommended range)		30-35m (inside) 35-45m (outside)	50m (inside) 55m (outside)	
circle width	4,0-6,0m	6,5-9,0m	8,0-10,0m	
central island	driveable	not driveable	not driveable	not driveable
number of lanes (circle /entry)	1 / 1	1 / 1	2 / 1 2 / 2	≥1 / ≥ 1
traffic control	sign-controlled	sign-controlled	sign-controlled	signal control

Figure 2. ***Figure 2*****. Main characteristics of different roundabout types (Vesper, 2009)**

3. SAFETY AND CAPACITY

Roundabouts are usually very safe intersections; serious accidents are quite seldom events. The main reasons for their high road safety level can be identified as follows:

- **Low number of conflict points**

Compact one-lane roundabouts and mini roundabouts have a lower number of conflict points in comparison with X-junctions as shown in *Figure 3*.

Furthermore, entering and circling vehicles are moving roughly in the same direction. As crossing and opposing movements do not occur at roundabouts, accidents with serious consequences can be avoided.

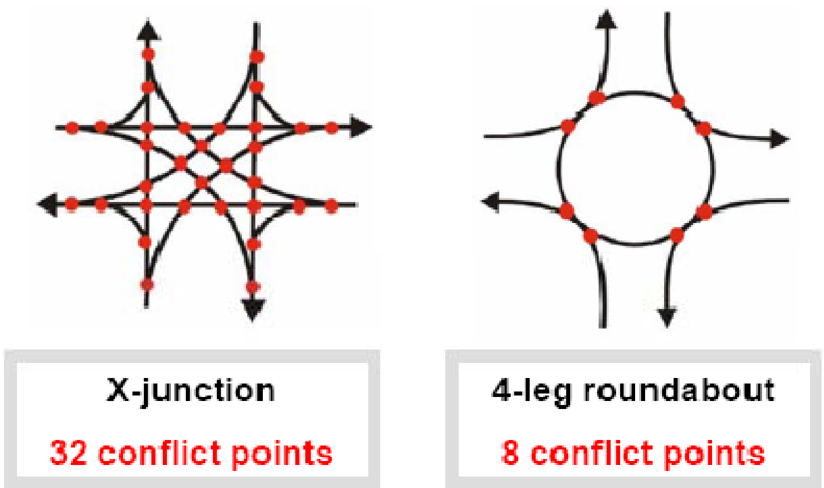

Figure 3. **Conflict points at a compact one-lane roundabout and an X-junction (Remark: all drawings and photos in this paper are shown according to left-hand traffic)**

However, large roundabouts with two lanes in the circle and two lanes at the entries and/or at the exits have significantly lower level of road traffic safety. Here the number of conflict points is larger. Especially problems with pedestrians in the entries, with motorcycles in the circle as well as lane changes before the exits lead often to serious accidents.

- **Low speed level at conflict points**

The speed level of vehicles at compact and mini roundabouts is normally significantly lower than at other intersection types (*Figure 4*). The low speed levels of vehicles as well as the small speed differences at conflict points have a direct impact on the number and severity of accidents. Here one should also consider that in case of lower speeds, the stopping distance of vehicles is also significantly lower.

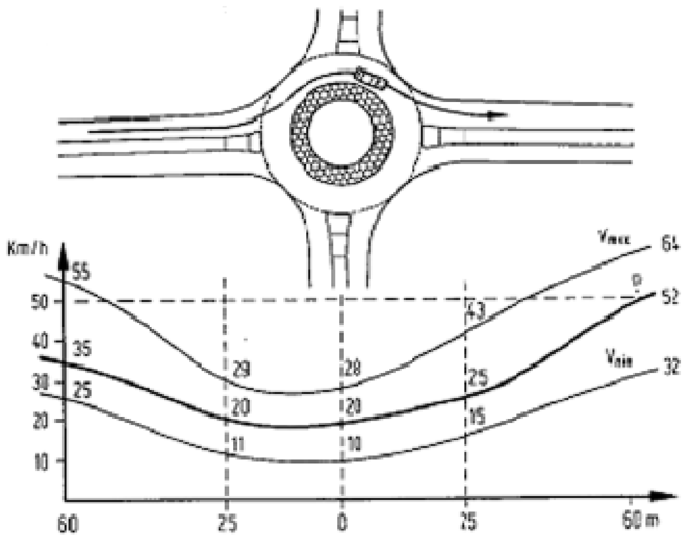

Figure 4. **Speed profile at a compact one-lane roundabout (according to FGSV, 2006)**

The low speed level at roundabouts is achieved mainly by rectangular guidance of entering vehicles and the deviation of vehicles in the circle (*see Figure 5*).

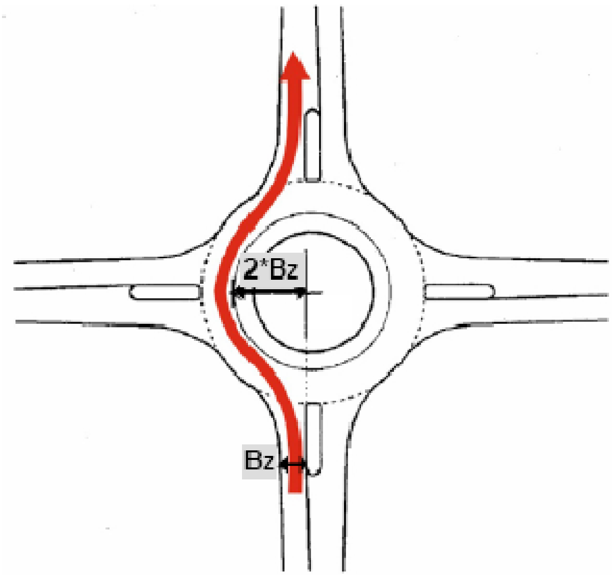

***Figure 5.* Deviation of cars in a roundabout by the central island (according to FGSV, 2006)**

Other safety benefits of roundabouts are:

- **It is easy to recognise and understand them**

Road users easily recognise and understand roundabouts. Especially the central island contributes to the good recognisability of a roundabout for approaching vehicles. Furthermore at roundabouts the priority rules are equal in each entry: entering vehicles have to give the priority to circling vehicles. The easy priority rules and the simple movements at roundabouts contribute mainly to the good performance of these intersections.

- **Pedestrians benefit from low speeds**

Pedestrians benefit from low speed level of vehicles in the entry and exit of roundabouts. Low speeds contribute normally to cooperative behaviour of vehicles and pedestrians.

Furthermore pedestrians are able to cross the road in two steps, because entry and exit-lanes are separated by a splitter island which can be considered as a refuge island.

4. CHOICE OF ROUNDABOUT TYPE

Total traffic volumes of up to 15,000 vehicles/day can be served normally by compact onelane roundabouts (up to 12,000 vehicles/day at mini roundabouts) without problems and with only short delays in the entries.

In case of higher total traffic volumes it is strongly recommended to conduct a detailed capacity analysis.

Typical ranges of capacity are shown in *Figure 6* for different roundabout types inside and outside built-up areas.

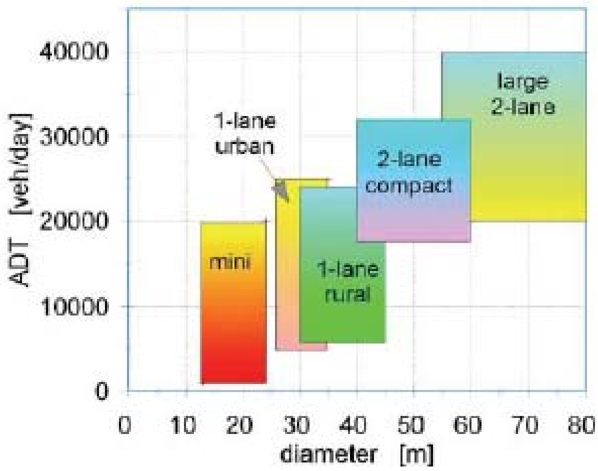

Figure 6. **Capacity of roundabouts by their size in terms of average daily traffic (Brilon, 2005)**

In general the compact one-lane roundabout is the standard solution of roundabouts inside as well as outside built-up areas. This type should be applied, whenever it is possible. Other types of roundabouts shall be used only if the compact one-lane roundabout is not applicable. If the available space to build a compact one-lane roundabout is not sufficient, a mini roundabout can be build alternatively (only inside built-up areas).

If the capacity of a compact one-lane roundabout is not sufficient and the required capacity can not be provided by the design of a by-pass, a compact two-lane roundabout can be built. In this case the capacity can be increased in the first step by the design of two lanes in the circle (not separated by marking) and in the second step by the design of two entry lanes. Furthermore, in general only one exit lane is allowed at compact roundabouts.

The choice of the appropriate roundabout type is summarized in *Figure 7.*

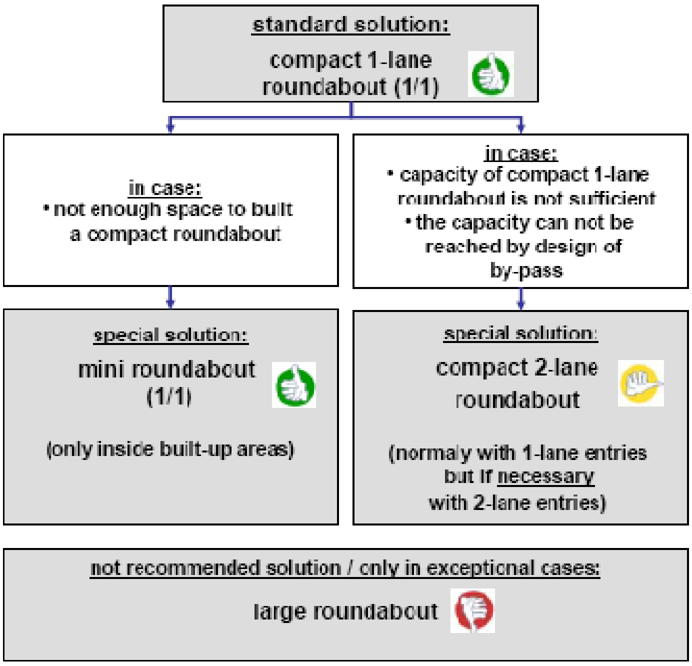

***Figure 7.* Choice of roundabout type (Vesper, 2009 according FGSV, 2006)**

It should be examined, whether a signalized junction could be designed instead of a compact two-lane roundabout, because the design of two-lane circles and two-lane entries can lead to various road traffic safety related problems as follows:

- In two-lane circles often serious conflicts occur between road users because of overtaking inside the circle. Additionally it is not unusual that trucks or cars push two wheelers like motorcycles away.
- It is more difficult for pedestrians to cross the two-lane entries of the intersection leg.

In general, large roundabouts are not recommended. A lot of bad experiences were made with large roundabouts in several countries in the last decades. Especially the negative impact on road traffic safety is a decisive argument to avoid this type of roundabout.

5. PRINCIPLES OF GEOMETRIC DESIGN

The general requirements on the design of intersections which need to be considered also at roundabouts, like perceptibility, recognisability, understandability, drivability and visibility are not discussed in detail here. The main elements of roundabouts are shown in *Figure 8.*

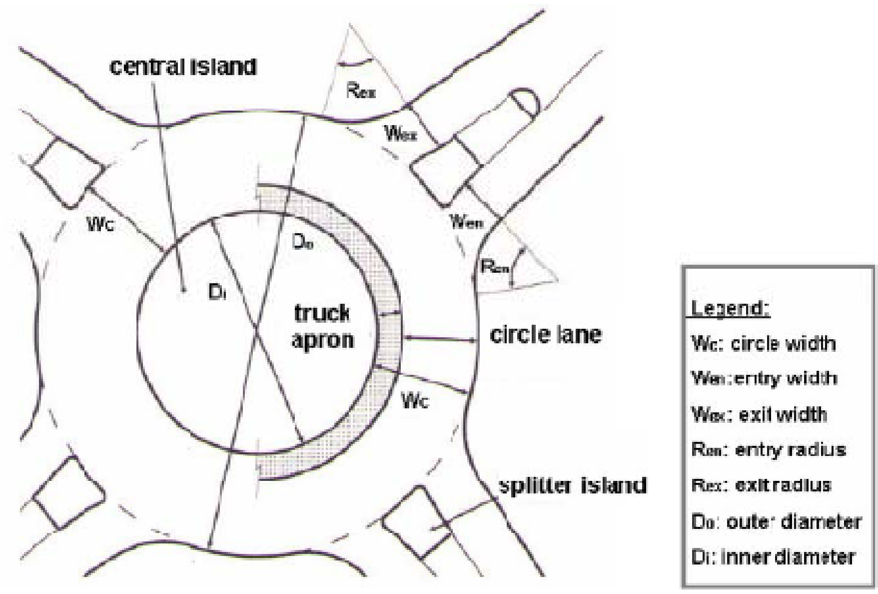

Figure 8. **Design elements of compact one lane roundabouts (according to FGSV, 2006)**

There are some specific requirements on the design of roundabouts which should be followed strictly, especially with the view on road traffic safety:

- entry lanes should be guided rectangular to the circular roadway (circle lane),
- obvious deviation of vehicles should be provided (cf. *Figure 5)*,
- axis of intersection-legs should point towards the centre of the circle,
- only round circular roadways (circle lanes) should be applied,
- only one lane exit-lanes should be applied,
- one lane entry-lanes should be preferred,
- one lane circular roadways should be preferred.

The right geometric design of the various elements is of crucial importance. The planned guideline will describe these rules in detail.

6. SOME EXAMPLES

Mini roundabouts

The mini roundabouts' outer circle diameter is between 13 and 22 meters. The central island should be driveable. The pavement of the central island should have a different surface and colour

Figure 9. **Mini roundabout, mirrored figures (FGSV, 2006 and Brilon, 2005)**

Compact one lane roundabouts

The compact one lane roundabouts' outer diameter is between 26 and 50 meters. The central island is not driveable, but there should be a driveable truck apron especially inside built-up areas. It helps the passage of trucks and longer vehicles.

Figure 10. **Compact one-lane roundabout inside built-up area, mirrored figures (FGSV, 2006, Brilon, 2005)**

Multilane Roundabouts

Multilane roundabouts have at least one entry or exit with two or more lanes and more than one circulating lane. They have larger capacity than one lane roundabouts. However they have safety problems, especially when vehicles from the inner lane want to leave the circle. Furthermore overtaking especially of two-wheelers inside the circle is often a serious road traffic safety problem.

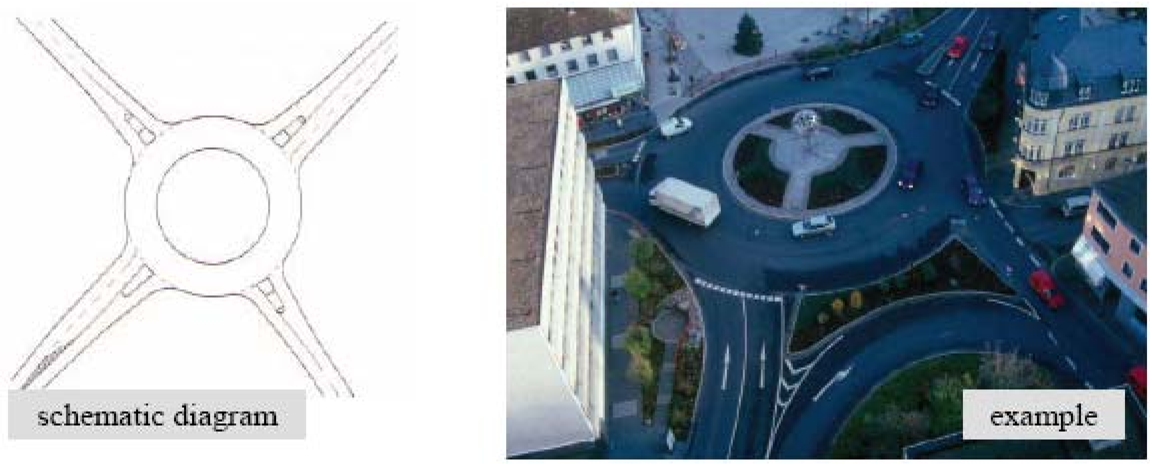

***Figure 11.* Compact two-lane roundabout inside built-up area, mirrored figures (FGSV, 2006, Brilon, 2005)**

***Figure 12.* Two-lane roundabout with typical conflict (Hóz, 2007)**

***Figure 13.* Accident investigation marks in a large multilane roundabout in Ayutthaya (Vesper, 2009)**

7. SITE SURVEYS IN THAILAND

As a part of the preparation of the design guidelines, site surveys were conducted in Thailand. It was found that the layout of existing roundabouts in Thailand differ significantly from the European ones. Furthermore the traffic behaviour of road users at roundabouts differs, too.

Therefore the goals of the survey were:

- to identify the local design solutions of roundabouts,
- to get acquainted with the local traffic behaviour at roundabouts,
- to collect data of the typical traffic volumes, mix, speeds, etc.

The first site visits were conducted in July and August 2009. During that time eight roundabouts were surveyed. Traffic volumes and traffic-mix were registered manually by visual observation. Speeds were measured on the approach lane and on the circulating roadway by speed camera. The geometric features of the sites including lane widths were also measured. Furthermore video recordings and photos were made in order to investigate the behaviour of road users.

Eight roundabouts in different regions in Thailand were selected for the first site surveys. Considering the timeframe of the surveys and the accessibility, the sites were selected near Bangkok, in Ayutthaya and in Chiang Mai. The roundabouts are different in their size, number of legs, number of lanes and location as shown in *Table 1*. As only one roundabout outside built-up area was studied, more such roundabouts will be surveyed in a later phase.

***Table 1.* Main characteristics of the selected roundabouts**

Site N°	Site	N° of legs	Inscribed diameter	Central island radius	N° of lanes	Size	Location inside/outside built-up area
1	Ayutthaya roundabout	4	48.90 m	12.80 m	2-3	Large	inside
2	Ayutthaya monument	4	81.30	15.90	4-5	Large	inside
3	Thammasat University	4	31.80	7.20	1+t.a.	Compact	inside
4	3 legs (3090-3089)	3	25.70	4.50	1+t.a.	Compact	outside
5	Rangsit University	4	46.00	14.90	1	Compact-big	inside
6	Clocktower (Chiang Mai)	4	41.00	9.80	1-2	Compact	inside
7	Asymmetric (Chiang Mai)	3	23.60	4.10	1	Compact	inside
8	Mini in Chiang Mai	3	18.90	2.15	1	Mini-compact	inside

*t.a.-truck apron

7.1 Speeds

Speed measurements were conducted at six roundabouts. As a preliminary result, *Figure 14* shows the average of the speeds of all vehicles at all the six junctions at four typical points: namely at the approach zone, at the entry, within the circle and at the exit.

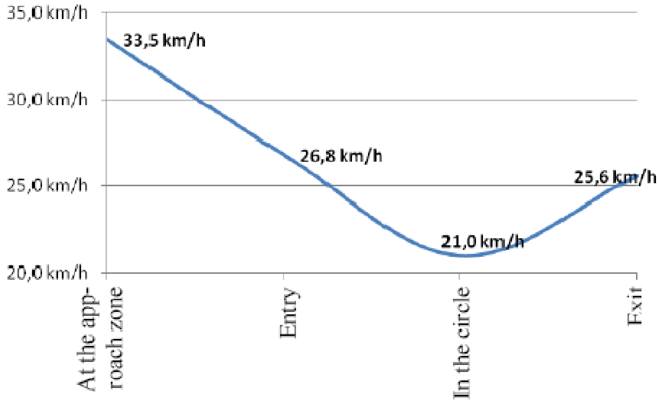

Figure 14. **Average speeds at four typical points at six roundabouts**

A more detailed analysis of the speed measurements will be given in the later phase of the project.

7.2 Traffic behaviour

Based on 15 minutes long video recordings, entering and leaving vehicles were observed at each intersection leg of seven roundabouts. Furthermore, conflict situations as well as irregular movements were registered. Conflicts were defined as situations requiring sudden action from the participants (braking, direction change, stop or run). Irregular movements were defined as manoeuvres not conforming to traffic rules but not requiring sudden action. Conflicts and irregular manoeuvres were classified in several groups. The number and ratio of such movements is summarized in *Table 2*. The conflict ratio was about 0.3% of all vehicles, whereas the ratio of irregular manoeuvres was about 8%. Sites No 2 and 3 have shown a definitely higher irregular ratio than the other sites. These differences will be analysed in the later phase of the project.

Table 2. **Conflicts and irregular movements at selected roundabouts**

Site N°	Site	Vehicles/ 15 min	Conflicts	Irregular movements	Conflict ratio	Irregular ratio
1	Ayutthaya roundabout	1586	2	99	0.1%	6.2%
2	Ayutthaya monument	776	12	126	1.5%	16.2%
3	Thammasat University	510	1	61	0.2%	12.0%
4	3 legs (3090-3089)	365	0	23	0.0%	6.3%
5	Rangsit University	776	0	34	0.0%	4.4%
6	Clocktower (Chiang Mai)	397	0	25	0.0%	6.3%
8	Mini in Chiang Mai	448	1	26	0.2%	5.8%
Total		4855	16	394	0.3%	8.1%

8. PROBLEMS AND THEIR ORIGINS

From the observations, some general problems concerning irregular traffic manoeuvres and conflict situations were identified. It was found that the origins of these problems are either in the design of the investigated roundabouts or in the behaviour of the road users.

The problems below are marked with a) to j). Later these problems will be connected to their origins, to the specific goals to increase safety and to the solutions (measures) which support to reach the goals.

Problems: irregular manoeuvres and conflicts at the investigated roundabouts

a) Irregular traffic movements in the entry- and exit zones
b) Overtaking and passing manoeuvres in the circle
c) Overtaking and passing manoeuvres in the exit zone
d) Public transport vehicles stop for their passengers in the entry and exit lanes
e) Vehicle drive too close and therefore can hit the curb of the central island
f) Cutting the theoretical movement path, higher speeds in the circle and in the exit
g) Incoming vehicles do not give priority, vehicles in the circle are forced to stop
h) Vehicles stop in the circle, give way to incoming traffic, and block the upstream
i) entering traffic
j) Drivers do not give the priority to pedestrians at the crosswalk
k) Pedestrians do not cross the road at the marked pedestrian crossings. They prefer to cross within or near to the circle

Figure 15 shows the frequency of the various irregular movements as a total of the seven roundabouts studied. The two largest segments are the disobeying of priority rules between vehicles (44%) and the overtaking and passing manoeuvres in the circle (36%). Concerning the share of various problems, there are differences between the sites which will be analysed in the later phase of the project.

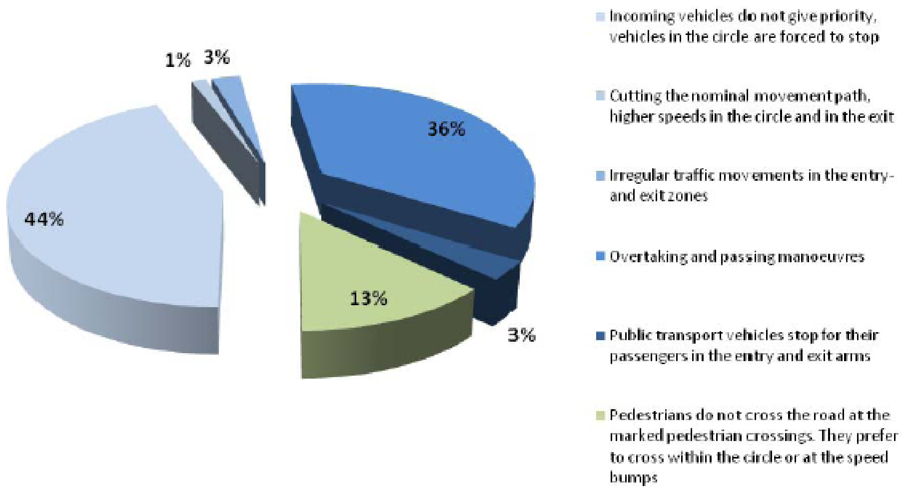

***Figure 15.* Share of the various irregular manoeuvres at the seven roundabouts studied**

Origins: design deficits at roundabouts and behavioural aspects of road users

Each problem should have at least one origin. The origins which were found to be relevant to the problems mentioned above are shown here, using the same letters in order to match the problems and the origins.

a) The splitter islands are often missing or they are not properly built, so the separation of the traffic streams is not realised.
b) The circular roadway is built too wide and in addition the truck apron has often no special surface; it is separated from the circular roadway with pavement marking only.
c) There is often too much available space at the exits.
d) There are no designated stops for public transport (mini buses and “red cars”).
e) The missing truck apron allows cars and especially two-wheelers to drive too close to the high curb of the central island. A high curb with a vertical face is not appropriate to separate the central island from circle.
f) The circular roadway is too wide; it allows vehicles a higher speed.
g) Drivers do not know the traffic rules or they do not recognise that it is a roundabout.
h) Drivers do not know the traffic rules or they do not recognise that it is a roundabout.
i) Due to the geometry, vehicles can arrive to the pedestrian crossing at a higher speed.
j) Pedestrians feel themselves in safety also in these zones.

About 13% of the observed irregular movements were related to pedestrians *(Figures 16-17).* Among vehicles, disobeying priority by entering vehicles is a frequent situation but vehicles in the circle are apparently prepared to resign of their priority *(Figures 18-19).*

Figure 16: **Pedestrian crossing the road between the yield line and the crosswalk at the entry of a roundabout**

Figure 17: **Vehicle does not give priority to pedestrian at a crosswalk at the entry of a roundabout**

Figures 18-19: **Vehicles stop in the circle and give the priority to entering vehicles**

9. GOALS AND PROPOSED SOLUTIONS

In order to increase traffic safety, the following specific goals and solutions are suggested. The letters again refer to the problems.

Goals: specific objectives to increase safety at the surveyed roundabouts

a) To separate the traffic streams in the entry and exit zones
b) To reduce the possibility of dangerous overtaking.
c) To ensure safe stops of the public transport vehicles.
d) To ensure the adequate distance between the vehicles and the curb of the central island.
e) The vehicles should pass the roundabout on the adequate paths.
f) To avoid that vehicles pass at high speeds.
g) The drivers should know and apply the traffic rules of the roundabouts
h) To reduce the number of the congestion situations that cannot explained with the high traffic volume.
i) To ensure the safe pedestrian traffic.
j) To ensure that pedestrians use the marked crosswalks.

Solutions: specific engineering measures at roundabouts and education of road users

a) The splitter islands should be correctly built.
b) Reduction of the width of the circular roadway.
c) Reduction of the available space at the exits.
d) To build designated stops for public transport vehicles.
e) To construct proper truck aprons and change the shape of curbs.
f) Reduction of the width of the circular roadway.
g) Education concerning the traffic rules at roundabouts
h) Education concerning the traffic rules at roundabouts.
i) Slow down vehicles by geometry.
j) To build proper splitter islands to ensure the safe crossing of the pedestrians.

Concerning the proposed specific engineering measures, there will be differences between the various sites which will be defined in the later phase of the project. The findings of the above mentioned and further site surveys will be used in the preparation of the guidelines. Workshops and trainings with Thai professionals will be performed in order to find the solutions best adapted to the local conditions.

10. CONCLUSION

It is acknowledged worldwide, that compact one-lane roundabouts and mini roundabouts are types of intersection which serve traffic on a high safety level. Similar experiences made in several countries around the world confirmed this statement in the last decades.

The authors are convinced that compact one-lane roundabouts and mini roundabouts will become widely accepted as a suitable intersection type in Thailand. Using this solution properly, road designers can contribute actively to the common challenge of reducing number and severity of road traffic accidents in Thailand.

The planned Thai design guideline for the "Design of Roundabouts" will foster the implementation of roundabouts in Thailand in the future. The design guideline will provide road engineers, road designers and other target groups in the design of road infrastructure necessary and useful knowledge about designing and constructing safe and efficient roundabouts in Thailand.

The planned design guideline will be developed based on the "Methodology of Design Guideline Implementation Based on International Technology and Knowledge Transfer" (cf. Vesper et al, 2010). This methodology will also be developed in the framework of the Thai- EC project "Improving Road Traffic Safety in Thailand – A Common Challenge for European and Thai Universities" by network partners of "NICE on RoadS".

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ANALYSIS OF STRESS, STRAIN AND DEFLECTION OF PAVEMENTS USING FINITE ELEMENT METHOD

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Abstract: Finite element method (FEM) is a numerical analysis technique to obtain the stress, strain and deflection of pavement layers. Analytical method usually uses elastic modulus and Poisson's ratio of the pavement materials as design parameters. The objective of this paper is to study the sensitivity of these variables in reducing the vertical surface deflections, the critical tensile strains at the bottom of the asphalt layer and the critical compressive strains on the top of subgrade using the finite element method. These variables can be used to improve pavement performance. It is expected that this study can be used as a guideline to assist design engineer to select the appropriate pavement structure.

Key Words: Vertical surface deflections_ flexible pavement_ finite element, pavement modulus

1. INTRODUCTON

Excess vertical surface deflections in flexible pavements have always been major concern and used as a criterion of pavement design. It is desirable to reduce the deflections as much as possible. This may achieved with or without the improvement of soil subgrade before construction. This paper deals with ways to reduce deflections by varying the design configuration, such as increasing the HMA modulus, the base modulus and the subgrade modulus. The objective of this paper is to study the sensitivity of these variables in reducing the surface deflections and the soil stress in flexible pavements.

The results of a series of parametric study to examine the effect of HMA modulus (E_1 varies), effect of base modulus (E_2 varies) and effect of subgrade modulus (E_3 varies) on the performance of flexible pavement with special emphasis on the deflection and stress. The pavement structure is a combination of subbase, base course, and surface course placed on a subgrade to support the traffic load and distribute it to the roadbed. Figure 1 presents a cross section of a basic modern pavement system, showing the major components.

Figure 1. Basic components of a typical pavement system

The objective of the present study is to investigate the effectiveness of two different methods in reducing vertical surface deflections (w_o) and the critical tensile strains in the asphalt layer (ε_t) or the radius strain at the bottom layer of HMA. The finite element method was adopted to evaluate the effectiveness of the two methods and the sensitivity of various factors.

Premature failure of flexible pavements has long been a problem in many roads with the strong increase in truck axle loads. To fully utilize each pavement material in an economic design, a pavement should generally have reasonably balanced design between the rutting and fatigue modes of distress. The purpose of this paper is to develop a methodology for achieving a reasonable balance between fatigue and rutting lives of flexible pavements. The methodology is based on the damage analysis concept which is performed for both fatigue cracking and rutting on different pavement modulus using FEM and KENLAYER program.

The first published FEM analysis of a pavement structure appeared in 1968 (Duncan et al., 1968), in which the authors used an axisymmetric formulation and specified the stiffness of each element in the granular layer as a function of the stresses in the element. The use of a FEM model allows the model to accommodate the load dependant stiffness of the granular and subgrade materials, although most models still use linear elastic theory as the constitutive relationship.

A field observation for evaluation of pavement surface conditions of roads network, showed that, rutting and fatigue cracking are considered the most important distresses surveyed due to high severity and density levels, and accordingly their high effects on the pavement condition. Flexible pavements should be considered to provide a durable, skid resistance surface under inservice conditions. Also, it is essential to minimize cracking and rutting in flexible pavement layers. To fully utilize each pavement material in an economic design, a pavement should generally have reasonably balanced design between the rutting and fatigue modes of distress. The increased rutting or decreased fatigue life of the flexible pavements may be attributed to the shortcomings of the application of flexible pavement analysis and the absence of attention to identify the pavement components that achieve a balanced section which gives equal pavement lives with respect to rutting and fatigue.

There are various modes in which the pavement fails. Cracking of the surface layer and permanent deformation of the pavement system which manifests as rutting on the pavement surface. Larger and more concentrated loads produce larger stresses and strains, with thicker layer carrying higher flexural stresses than thinner layers. In pavement analysis, loads on the surface of the pavement produce two strains which are believed to be critical for design purposes. These are the horizontal tensile strain; ε_t at the bottom of the asphalt layer and the vertical compressive strain; ε_c at the top of the subgrade layer. The design criteria will be used for an analytical approach of pavement design as shown in figure 2.

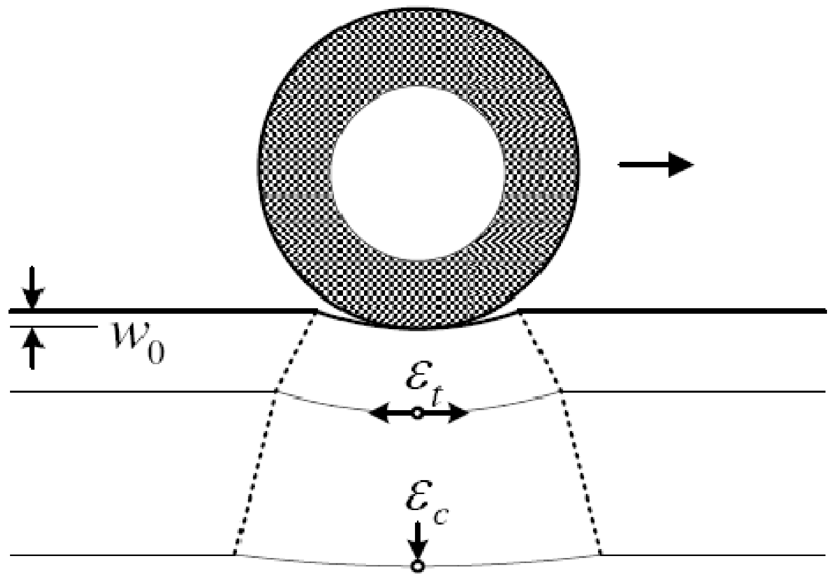

Figure 2. Failure modes and critical strains in flexible pavement

If the horizontal tensile strain; ε_t is excessive, cracking of the surface layer will occur, and the pavement distresses due to fatigue. If the vertical compressive strain; ε_c is excessive, permanent deformation occurs at the surface of the pavement structure from overloading the subgrade, and the pavement distresses due to rutting. Damage analysis is performed for both fatigue cracking and permanent deformation as follows:

1.1 Fatigue Criteria

The relationship between fatigue failure of asphalt concrete and tensile strain at the bottom of asphalt concrete layer is represented by the number of repetitions as suggested by Asphalt Institute in the following form:

$$N_f=0.0796 \left(\frac{1}{\varepsilon_t}\right)^{3.291} \left(\frac{1}{E_1}\right)^{0.854} \quad (1)$$

Where
N_f : number of load repetitions to prevent fatigue cracking.
ε_t: tensile strain at the bottom of asphalt layer.
E_1 : elastic modulus of asphalt layer.

1.2 Rutting Criteria

The relationship between rutting failure and compressive strain at the top of subgrade is represented by the number of load applications as suggested by Asphalt Institute in the following form:

$$N_r= 1.365\times10^{-9} \left(\frac{1}{\varepsilon_c}\right)^{4.477} \quad (2)$$

Where
N_r : number of load repetitions to limit rutting.
ε_c : vertical compressive strain at the top of subgrade.

2. METHOD OF ANALYSIS

A typical cross section consists of asphalt layer thickness (d_1 = 4 in) with elasticity modulus (E_1=200,000 psi), and base layer thickness (d_2 = 8 in) with elasticity modulus (E_2=20,000 psi), resting on subgrade with elasticity modulus (E_3=2,500 psi) is considered a section with reference components. Different probable cross sections that may be used in Thailand Roads are considered for analysis through varying the reference components. That is, E_1 is varied from 200,000 to 1,000,000 psi, while E_2 is varied from 20,000 to 750,000 psi and E_3 is varied from 2,500 to 15,000 psi. Materials in each layer are characterized by a modulus of elasticity (E) and a Poisson's ratio (υ). Poisson's ratio; υ is considered as 0.35, 0.30 and 0.40 for asphalt layer, base course and subgrade, respectively. Traffic is expressed in terms of repetitions of single axle load 18-Kip applied to the pavement on two sets of dual tires. The investigated contact pressure is 100 psi. The dual tire is approximated by two circular plates with radius 4 in and spaced at 14 in center to center. The detrimental effects of axle load and tire pressure on various pavement sections are investigated by computing the tensile strain (ε_t) at the bottom of the asphalt layer and the compressive strain (ε_c) at the top of the subgrade. Then, damage analysis is performed using the two critical strains to compute pavement life for fatigue cracking and permanent deformation (rutting).

Sensitivity Analyses demonstrate the effect of various parameters on flexible pavement. The analysis is being carried out using the finite element computer package VisualFEA. The results indicate that displacements under loading are the closest to mechanistic methods. A research study is being undertaken to incorporate the realistic material properties of the pavement layers and the moving traffic load, in the analysis of the flexible pavement, using the finite element method. For comparison, flexible pavement is typically taken as a multilayered elastic system in the analysis of pavement response, using KENLAYER.

As with models for the prediction of resilient response, there are a large number of models that have been proposed to model the Permanent Deformation (PD) of granular materials. These models appear to be either based on: observed performance and are expressed as function of the number of load applications/cycles and the applied stress state. Duncan and Chang (1970) proposed a hyperbolic model for predicting plastic strains from triaxial tests as a function of confining and deviator stresses, cohesion, the angle of internal friction and a ratio of compressive strength to an asymptotic stress difference. Well-known geotechnical models of this type are the Cam-Clay (Schofield and Wroth, 1968) and Drucker-Prager (Drucker and Prager, 1952) models. The Mechano-Lattice (ML) method of analysis (Yandell 1971), determines the elastic and plastic response of the system as a wheel rolls across the surface of the model. The pavement structure is modelled as a series of springs in a lattice framework. The observation from repeat load triaxial testing that materials have a higher secant modulus on unloading than loading is used to develop the plastic strains within the structure. Yandell (1971) and Yandell and Behzadi (1997) report the analysis of ALF trials from Australia and pavements design using the Shell Pavement Design method using the ML framework. The plastic strains predicted by the ML method are comparable to the measured plastic strains/ruts.

The geometry of the hypothetical problem is shown in figure 3. Table 1 shows the typical pavement material properties. The material properties are shown in table 2. A total of 11 cases were analysed. The finite element mesh is shown in figure 4. This analysis is based on the assumption that all layers are linear elastic. Although HMA layers are viscoelastic and base layers are nonlinear elastics.

Table 1. The typical pavement material properties

Material	E (psi)	Poisson's ratio	Unit weight (Ib/ft^3)
AC surface	150,000	0.4	150
Soil-cement base	750,000	0.25	140
Crushed rock base	60,000	0.4	140
Soil-aggregate subgrade	30,000	0.4	125
Selected material	15,000	0.4	115
Subgrade			
(1) CBR=2	3,000	0.4	-
(2) CBR=4	6,000	0.4	-
(3) CBR=6	9,000	0.4	-

Table 2. Pavement material properties use in this analysis

Material	E (psi)	Poisson's ratio
AC surface	200,000 to 1,000,000	0.35
Base	20,000 to 750,000	0.3
Subgrade	2,500 to 15,000	0.4

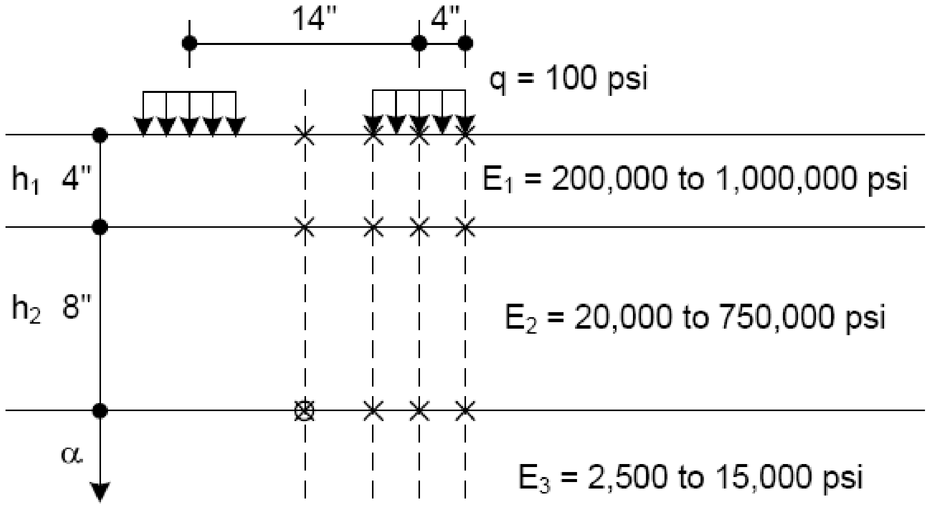

Figure 3. The geometry of the hypothetical problem

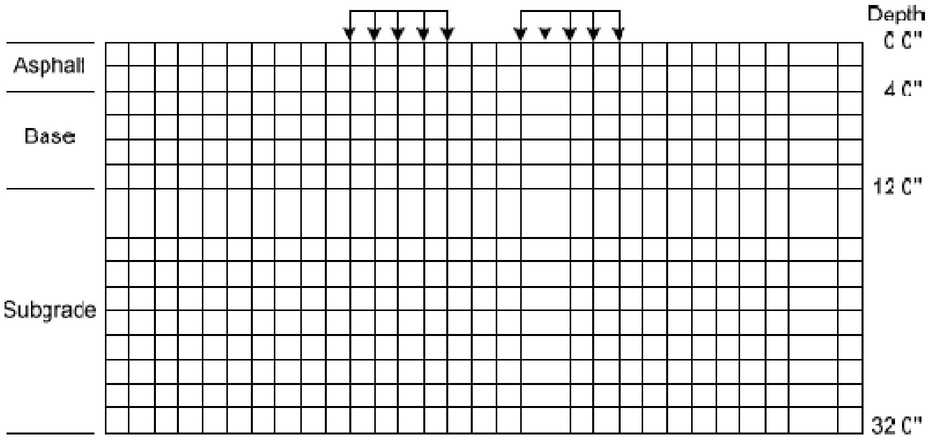

Figure 4. Typical mesh for the hypothetical problem

3. EFFECT OF LAYER MODULUS

This study is to compare flexible pavement performance using FEM and KENLAYER computer program, respectively. Comparison of the output has been made to determine the governing distress and deterioration models. Figure 5 and 6 show contour plot for displacement and vertical strain of FEM, respectively. The results of the analysis which performed on the investigated pavement cross sections using FEM and KENLAYER are presented in figure 7. As can be seen in figure 7, the vertical deflection reduce as modulus increases at all values of E. It is also can be noticed that, w_o has no sensitivity with the variation of E_1, compared with E_2 and E_3 which is high sensitive to the variation of E_3.

The investigated pavement components are elasticity modulus (E_1, E_2 and E_3) for asphalt layer, base layer and subgrade elasticity modulus, respectively. The results of pavement analysis showed that E_3 are the key elements which control the equilibrium between fatigue and rutting lives (N_f and N_r, respectively). That is because, increasing E_3 sharply increases N_r, and don't affect in N_f. The study also concluded that, increasing E_2 and E_1 mildly increases N_f and Nr. It can be said that, E_3 is the most effective component in pavement structure for increasing pavement life, followed by E_2 (high quality base).

Table 3. Parametric studies in this study

Case	E1(psi)	E2(psi)	E3(psi)	$w_o(10^{-4})$	$\varepsilon_t\ (10^{-4})$	$\varepsilon_c\ (10^{-4})$
1	200,000	20,000	2,500	1.558	4.75	2.319
2	400,000	20,000	2,500	1.468	5.73	2.094
3	600,000	20,000	2,500	1.406	5.48	1.933
4	800,000	20,000	2,500	1.360	5.06	1.813
5	1,000,000	20,000	2,500	1.320	4.64	1.719
6	200,000	40,000	2,500	1.351	1.17	1.289
7	200,000	60,000	2,500	1.260	0.29	0.909
8	200,000	750,000	2,500	1.020	1.69	0.109
9	200,000	20,000	7,500	0.753	2.69	2.200
10	200,000	20,000	15,000	0.499	1.50	2.150
11	200,000	60,000	15,000	0.033	1.16	0.748

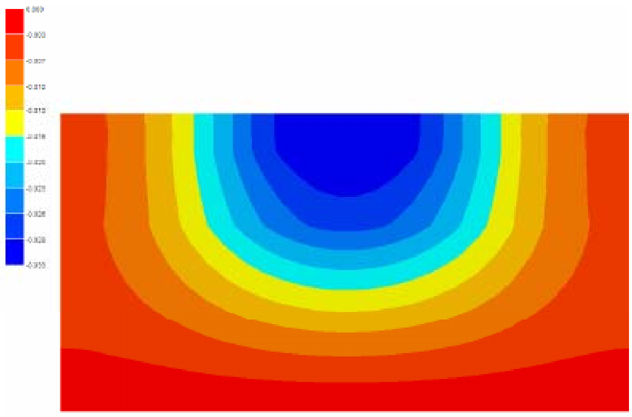

Figure 5._Contour plot for_displacement

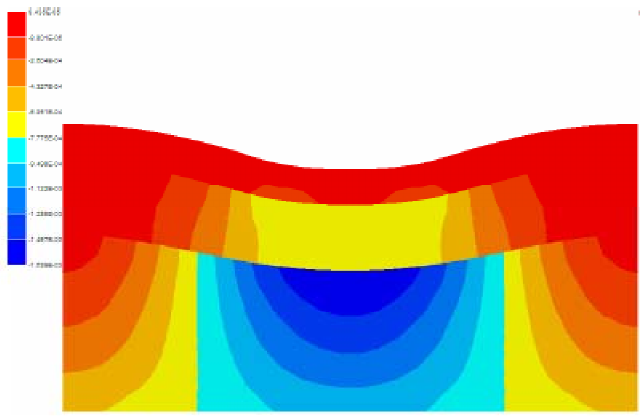

Figure 6. Contour plot for vertical strain

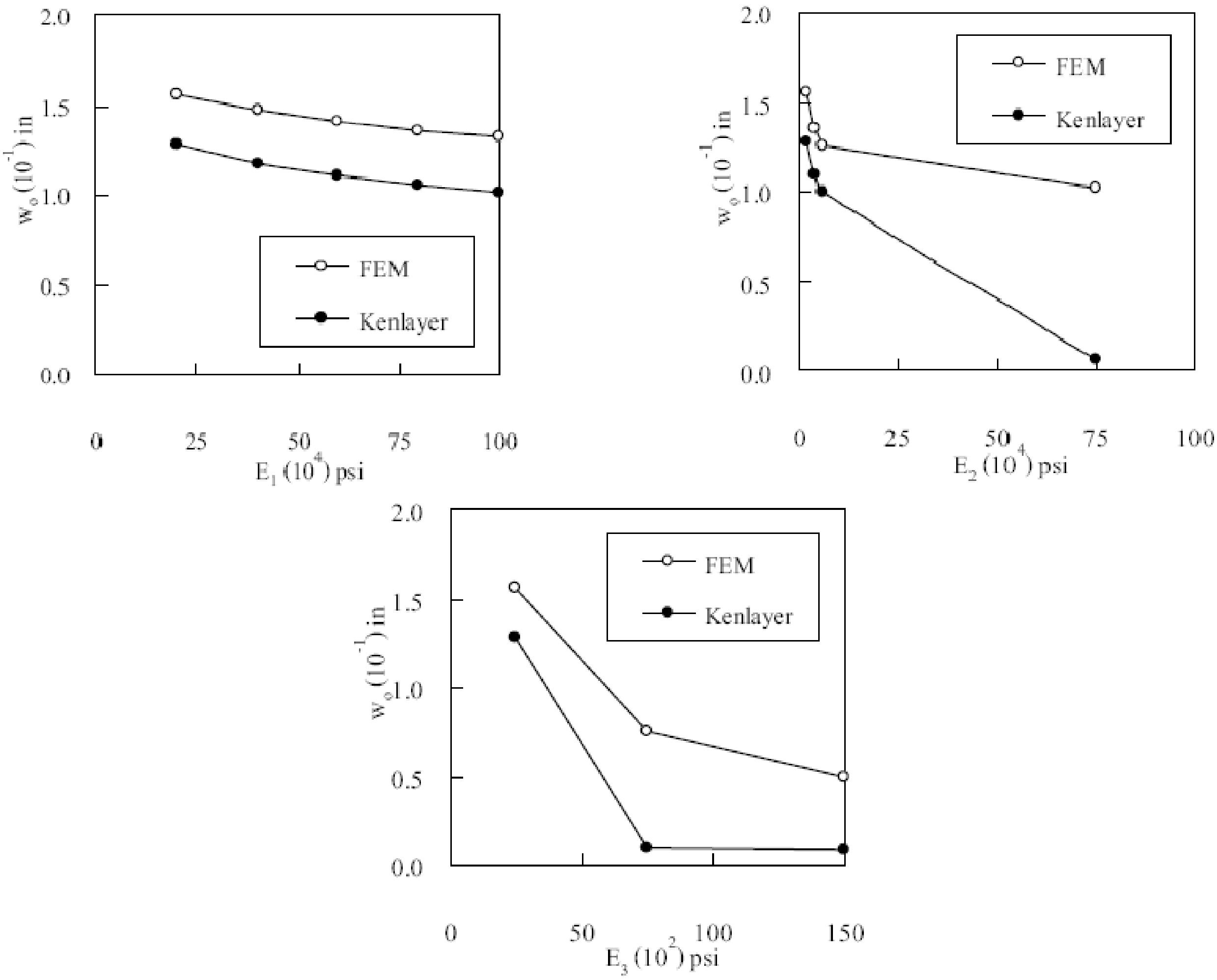

Figure 7. Effect of modulus on vertical deflection (w_o)

4. CONCLUSIONS

Based on the analysis of results of this study, the following conclusions are drawn:

1. E_3 is the key elements which control the excess vertical surface deflection in flexible pavement.
2. E_2 and E_1 have mildly effect on the excess vertical surface deflection in flexible pavement.
3. The value of E_3 = 7,500 psi are the optimum values which achieve balanced sections at all values of E_1 and E_2.

It is also, recommended to complete this work by conducting economical analysis to define the optimum pavement components from economic point of view.

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Private Motorized Urban Mobility and Its Impact on Inspection and Maintenance Program in Indonesia

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Abstract

In order to response the degradation of urban air pollution from passenger car emission, the Government of Indonesia and local government of several cities in Indonesia initiated Inspection and Maintenance Program for in-use passenger car. This paper describes a comparison analysis of vehicle characteristics and urban city's indicators which influence to emission test results of passenger car emission. We apply bivariate probit model for the likelihood of CO and HC emission violations given a set of vehicle characteristics. Data of passenger car emission measured randomly during on-road emission measurements at ten cities in Indonesia in 2006 and 2007. The engine size, fuel system, vehicle maintenance quality and passenger car travelled kilometer per year play significant role in determining the probability of emission test failure. Furthermore, using dimensionless analysis with non-linear regression, we found GDP per capita and road saturation level influence personal vehicle mobility per capita per year at city level data. In order to pass vehicle emission test, empirical study confirm that low mobility caused by high congested city is worse than high mobility supported by low congestion level of traffic situation. To evaluate vehicle's emission performance, instead of vehicle characteristics, we should consider other external factors of traffic situations.

Keywords: Bivariate Probit, Non-linear least square, Passenger Car, Urban Indicators

1. INTRODUCTION

Facing severe air quality deteriorations, in 2003, government of Indonesia issued a type approval standard for new vehicles which will be enacted totally in 2007. Simultaneously, the government of Indonesia also improved the idle emission standard for in-use vehicles in 2006 which revised the previous 1995's standard. Some local governments took part into this program by creating and implementing their standard depends on the local situations. Example, the local government of Jakarta issued a bylaw on air pollution controls from mobile sources, which took effect since February 2006. Bylaw stipulates that all private car owners must get their vehicles' emission tested biennially *(1*). This policy is main part of popularly known as the inspection and maintenance (I/M) program. As an incentive, the bylaw states that the emissions certificate is required for extending the vehicle's registration *(2*). In order to pass the emissions test, the vehicle emissions should be lower than the in-use vehicle standards set by a decree.

Passenger car emission control program aims to reduce emissions to a level necessary to maintain environmental quality at desired levels. To address emissions from mobile sources, an integrated approach is needed, because some of the measures can only be effective if they are enforced along with other measures. Tightening new passenger car emission standards should be accompanied by concomitant tightening of in-use standards for those newer model vehicles. These standards form the basis for routine passenger car emission inspection carried out as part of the inspection and maintenance (I/M) program.

However, there have been ongoing debates on the effectiveness of I/M program to reduce the mobile emissions. Studies by Hubbard *(3)*, Wasburn *et. al. (4)*, and Bin *(5)* have criticized I/M programs based on three points mainly. First, it has been argued that I/M programs are an inefficient use of resources to achieve air quality objectives. It is also inconvenient to the vast majority of the driving population. Second, I/M program does not the most effective way to identify gross polluting vehicles. Especially, idle-mode test, the I/M test procedure does not account for the real world driving conditions such as acceleration and deceleration cycles. Thus vehicles passing the emissions test may still be gross polluters in the real world driving conditions. Third, the programs have mainly failed to provide drivers with incentives to minimize their vehicle emissions *(4)*. Additionally, many drivers tamper with engines and emissions control procedures in order to pass the emission test because of high costs of repair or maintenance costs of high emitting vehicles

Related to the engine and emission control devices, the maintenance is an important factor. Passenger car emission control systems begin to function improperly while the vehicles are still being driven. Combustion-powered vehicles naturally tend to deteriorate with age and usage. Thus, old vehicles have become a major problem in many metropolitan areas. Also, minor malfunctions in the air/fuel or spark management system can increase emissions significantly. For all these problems, it is important to maintain a passenger car regularly for detecting malfunctions giving rise to emissions *(6)*.

Implementation of in-use passenger car emission standards and also passenger car emission testing does not usually result in additional direct costs for governments. Usually, implementation costs transferred to passenger car owners. In case of several cities in Indonesia, the local government endorse the private passenger car mechanic workshops to perform the I/M program. The private passenger car owner can do the emission test and passenger car maintenance in order to meet the allowable standard. Considering the passenger car populations in Indonesia, their rapid growth rate and its usage especially in urban areas, results of this study can contribute to evaluate current situation and useful for local government to improve local strategies for passenger car emissions reduction programs.

In this study, we first attempt to analyze in-use passenger car emissions based on the data collected by idle-mode emissions test measurements at 10 big cities in Indonesia which are Jakarta (JKT), Yogyakarta (YGY), Surabaya (SBY), Balikpapan (BPN), Makassar (MKS) Batam (BTM), Manado (MND), Mataram (MTRM), Padang (PDG) and Pontianak (PNTK). By using data collected from sampled vehicles drawn randomly at those 10 cities, we can compare actual emission conditions of in-use passenger car with Indonesian's standards. Bivariate Probit analysis is conducted for the likelihood of carbon monoxide and hydrocarbon emission violations given a set of passenger car characteristics. This methodology finds the effects of characteristics such as carburetor/injection system, engine size, passenger car travelled kilometer per year and air-fuel ratio which assume represent dummy variable of passenger car maintenance on the likelihood of emissions test failure. Furthermore, we analyze the relationship between urban individual mobility, passenger car travelled kilometer per year, and urban indicators such as GDP per capita, urban passenger car road saturation level, and vehicle ownership saturation at city level. We assume that the difference probability to pass the emission test of observed passenger car have been influenced by personal urban mobility pattern which affected by urban city's characteristics and situations. Output of this study can be used to support our central government of Indonesia in order to evaluate city's performance on I/M program which considered as component of city's environmental management rating program namely Adipura.

2. METHODOLOGY

2.1 Idle Emission Measurement of in-use vehicles

To perform idle-emissions tests, we refer to Indonesian Standard SNI 09-3678-1995 which was already revised to be SNI 19-7118.3.2005. These Indonesian standards developed based on International Organization for Standardization (ISO) 3930/OIML R99-instrument for measuring vehicle exhaust emission 2000- and United Nation for Economic Commission for Europe (UN-ECE). To prepare idle-emission test, passenger car exhaust pipe shouldn't have any leakage, under normal temperature of engine and the ambient temperature in between $20_{o}C$-$35_{o}C$. Idle conditions means the passenger car engine working without any acceleration of fuel system, neutral transmission position for manual type of passenger car, neutral transmission or parking position for automatic passenger car. At the same time, other passenger car accessories which influence to engine rotation were shut down. Vehicles exhaust gas measured by a gas analyzer to obtain the concentration or emissions levels of CO (%) and HC (ppm).

As well, emissions level is also influenced by the driving cycles. Many factors may influence on-road driving cycle and levels of passenger car exhaust pollutants. Driving cycles of urban areas differed significantly from rural areas *(7)*. Urban cycles has shorter travel distance, lower travel speed, more idle time, and lower acceleration/deceleration time than rural ones. Urban areas generally have more congested traffic, intersections and traffic signal than do rural areas. Accordingly, urban driving cycles generally consumes more fuel (approx. 30% more per km) than does rural driving but the emission levels in urban driving differ insignificantly from those in rural driving *(7)*.

Road traffic in big cities in Indonesia is characterized with high congestion levels during day times. Thus, there is great number of vehicles operating at idle or stop-and-go driving conditions. It is known that vehicle exhaust emissions of NOx, CO, HC and particles are different at driving conditions, being the highest during acceleration *(8)*. Nevertheless, we can assume that emission test results can be used to represent the real world conditions at sites over-congested traffic that result in long idling times. A vehicle may have over 25% of its time spent in the idle mode *(9)*.

2.2 Bivariate Probit model for in-use vehicles exhausts emissions

The bivariate probit regression analysis used to examine the likelihood of CO and HC emission violations. There are two types of vehicles (carburetor and injection) which mentioned in state Ministry of Environment Decree No 13 Year 1993 which was already revised in 2006. The maximum allowable idle emissions limit value of CO is 4.5% volume and maximum HC value is 1200 ppm. Some local government, try to differentiate emission standard based on engine fuel system categories, in this study we refer to our national standard as mention in above. Other secondary data contain information on the various passenger car characteristics of tested passenger car, such as vehicle registration number, manufacturer, make and model as well as model year, engine fuel system, odometer reading, lambda, and passenger car types. In the model, emission test violation is defined as the effect of passenger car characteristics such as engine size, engine fuel system and running kilometer of passenger car. Other dummy variable of maintenance quality was determined by air-fuel mixture ratio (AFR) and its deviation to the normal standard value of AFR which assume represent the maintenance quality of car. Using all independent variables, we propose a Bivariate binary Probit regression model of the emission test failure. Bivariate binary Probit regression model depends on simultaneous observation of two discrete binary observed-dependent variables, i.e., y_{i1} *and* y_{i2}, that indicates the emissions test failures of CO and HC. Based on the observed dependent variables that take binary discrete values, underlying continuous dependent variables, z_{i1} and z_{i2}, can be expressed as:

$$\begin{aligned} z_{i1} &= \boldsymbol{\beta}_1' \mathbf{x}_{i1} + \varepsilon_{i1} \\ z_{i2} &= \boldsymbol{\beta}_2' \mathbf{x}_{i2} + \varepsilon_{i2} \end{aligned}, \quad y_{ij} = 1 \text{ if } z_{ij} > 0,\ y_{ij} = 0 \text{ otherwise},\ j = \{1, 2\} \tag{1}$$

where i denotes an observation; **β** and **x** stand for the vectors of parameters and the independent variables respectively; ε_{i1} and ε_{i2} are random variates distributed jointly as standard Bivariate Normal and a free correlation parameter, ρ, i.e., BNV [0,0,1,1, ρ]. Based on the equation given above, the log- likelihood function of the sample can be given as:

$$\log L = \sum_i \log \Phi_2 \left[q_{i1} \boldsymbol{\beta}_1' \mathbf{x}_{i1}, q_{i2} \boldsymbol{\beta}_2' \mathbf{x}_{i2}, q_{i1} q_{i2} \rho \right] \tag{2}$$

where Φ_2 stands for the standard Bivariate Normal distribution; q is an indicator variable such that $q_{im} = 2y_{im}-1$, $m = \{1, 2\}$. Based on data collected by the on-road measurement at Jakarta, Surabaya and Bandung in 2004, the model is estimated by using LIMDEP Version 8.0 econometric software *(10).*

Passenger car running kilometer per year calculated by divide the actual odometer reading for each samples and vehicle age. According to vehicle model year and passenger car running kilometer per year samples distribution, we classify all data into six groups (Table 1). Based on the engine fuel system, we categorized two groups of carburetor and injection cars. For dummy variable of maintenance quality, we use air-to-fuel ratio measured from each samples and classified them into five categories: very good, good, moderate, bad and very bad based on their deviation if compare to the reference value (one). Finally, all data sources grouped depend on sampling locations and we use Jakarta's data as the reference in order to make a comparison analysis among cities.

Table 1 Variable definition of Emission Indicators, Vehicle Characteristics and Urban CityIndicators

No	Indicator	Driver
A	Emission Indicator	
	1. Carbon Monoxide (CO)	Carbon monoxide measured by the percent of total volume of emission gas. Compare to National Standard (1 if passed the emission test, other=0)
	2. Hydrocarbon (HC)	Hydrocarbon measured by parts per million. Compare to National Standard (1 if passed the emission test, other=0).
B	Private Vehicle Characteristic	
	1. CARB	Carburetor Cars=1, Other=0
	2. RKTYRCLS	Private Passenger Car Running Kilometer per year. Calculate by observed odometer reading and vehicle age. Divided into six class: 1<10000 km/yr; 10001<2<20000 km/yr; 20001<3<30000 km/yr; 30001<4<40000 km/yr; 40001<5<50000 km/yr; 6>50001 km/yr
	3. ENGSZCLS	Engine Size Class (cc). 1 < 1000 cc; 1001<2<1500 cc; 1501<3<2000 cc; 4>2001 cc
	4. IMCODE	Dummy Variable Maintenance Quality. Calculate by using measured Air to Fuel Ratio. Very good ($0.95\leq \lambda <1.05$); Good ($0.9\leq \lambda <0.95$ or $1.05\leq \lambda <1.1$); Moderate ($0.85\leq \lambda <0.9$ or $1.1\leq \lambda <1.15$); Bad ($0.8\leq \lambda <0.85$ or $1.15\leq \lambda <1.2$); and Very bad ($\lambda <0.8$ or $1.2\leq \lambda$)
C	Urban Indicator	
	1. Demographics	Total population of the metropolitan or city area
	2. Infrastructure	Total area of Metropolitan or city area (km^2) Total length of metropolitan road network (km)
	3. Private Passenger Vehicles	Number of passenger cars on register (unit) Total annual vehicle kilometers of travel by passenger cars (km/year)
	4. Economics	Gross Domestic product per capita of metropolitan or city area

2.3 Private Motorized Urban Mobility

Private motorized mobility, in this study define as private cars, is based on vehicle kilometers of travel by passenger car, which in turn is a surrogate for urban transport emission, urban air quality is directly linked to urban structure. There is considerable literature detailing in the relationship between a city's urban form and motorized travel behavior and patterns. A wide ranging review of literature reveals that there are a set of economic, physical planning, transport infrastructure and transport service and usage factors that are considered drivers and indicators of private motorized mobility *(11)*. He establishes a model for private motorized mobility by applying dimensional analysis to a selection of key drivers which explains mobility in cities. The potentially complex matter of understanding a city's level of private transport use, is thereby reduced to a small number of reasonably accessible urban data items as already mention in table 1.

Dimensional analysis is a powerful technique that can be used to develop our understanding of any system when we know the controlling parameters, but don't have a model through which relate these parameters. Dimensional analysis is based on the premise that a dimensionally homogenous relationship between the controlling parameter is independent of the choice of units and any relationship so derived will be completely general and valid for all observers *(11)*. It is underpinned by the inherent assumption that all of the controlling parameters have been identified and that dimensionless ratios of these are related to each other by some as yet unknown function.

Based on the review, in this study, the underlying drivers of a city's private motorized mobility, together with the indicators of that mobility are listed in table1. These variables have been selected based on the previous study *(11)* and used on the basis that data are readily available in Indonesian cities. These variables have been chosen on the basis that:

- Population which defines the characteristics and size of a city.
- Metropolitan land area defines physical size of city.
- The total length of a city's road network is indicative of the extent to which transportation, especially private transportation is catered for.
- The number of passenger cars with their corresponding annual kilometers of travel is the direct indicators of a city's private motorized mobility.
- The economic indicators reflect the wealth of the city and its capacity to afford private motorized mobility.

A city's urban form exerts an important influence on its transportation patterns *(11)* and that some representation of a city's urban form should be incorporated in any model of private motorized mobility. On the other hand, increasing private motorized mobility is ultimately limited by the available infrastructure, be it road ability of motor vehicles. The availability of this infrastructure is clearly a physical limitation on the ultimate growth of private motorized mobility. This suggests the need for a variable that expresses the availability of such infrastructure across the city area. Ingram and liu *(12)* suggest that vehicle road use saturates at 550 vehicles per kilometer of road whereas Dargay and Gately *(13)* have assumed that vehicle ownership saturates at 0.85 vehicles per capita. And so, private car infrastructure saturation was accounted for through defining two dimensionless parameters as *(11)*:

$$\Pi_{rds} = \alpha_c / (550\lambda_{ro}) \qquad (1)$$

$$\Pi_{vehicles} = \alpha_c / (0.85\beta_p) \qquad (2)$$

Where α_c is the number of private cars on register, λ_{ro} the length of metropolitan road network, β_p the population of metropolitan, Π_{rds} the vehicle road saturation level of the city and $\Pi_{vehicles}$ is the vehicles ownership saturation level of city.

On the assumption that these dimensionless Π groups represent all of the available parameters for urban private motorized mobility in Indonesia (Table 1), the unknown functional relationship linking them was found by non-linear regression *(11)*. In this study, the simplest approach of a dimensionally homogenous equation linking a city's private motorized mobility to a number of independent dimensionless ratios formed from the drivers of its urban mobility by assuming that the unknown function could be represented as:

$$\Pi_{mob1} = f\,(\mathrm{GDP},\ \Pi_{rds},\ \Pi_{vehicles}) \qquad (3)$$

where the form of function was optimized through the iterative elimination of individual Π groups using the statistic t, P. Non-linear regression function in LIMDEP *(10)* was used to refine the simplest optimized form of dimensionally homogenous equation linking a city's private motorized mobility to a number of independent dimensionless ratio from the drivers of urban mobility.

3. DATA

Total passenger car (M/C) population in Indonesia is around 4 Millions in 2002 *(14)* and total annual sales in 2008 is 0.6 million per year *(15)*. Ten cities were selected as the onsite idle emission measurement spots (Figure 1). Jakarta is the capital city of Indonesia which has total administrative area 654.85 km^2 and total population around 7.9 millions. Total passenger car population is around 1.5 million or 30% of total vehicles population in 2006 *(16)*. Yogyakarta is located at central java province which has 32.5 km^2 of administrative area and total populations around 0.5 millions. Total passenger car population is 35 thousands units or 17.5% of all vehicles population in 2006. Surabaya is the second biggest city in Indonesia and also the capital city of East Java Province. Surabaya has 326.36 km^2 of administrative area and around 2.7 millions of population. Passenger car population in Surabaya is around 800 thousands units equal to 72.9% of total vehicles population. Surabaya is the second biggest city in Indonesia and also the capital city of East Java Province. Surabaya has 326.36 km^2 of administrative area and around 2.7 millions of population. Passenger car population in Surabaya is around 200 thousands units equal to 20% of total vehicles population. Makassar is the biggest city in Eastern part of Indonesia and also the capital city of South Sulawesi Province. Makassar has 326.36 km^2 of administrative area and around 1.2 millions of population. Passenger car population in Makassar is around 75 thousands units equal to 18% of total vehicles population. Batam located in the island closed to Singapore and total administration area of Batam is 415 km^2. Population of Batam around 727878 people and car population in 2007 around 33 thousands car which is 20% of total motorized vehicles. Manado located in the same island with Makassar (Sulawesi Island) and also the capital city of north Sulawesi province. Manado has 157.2 km^2 of administration area and 422 thousand people live in the city. Car population is around 19 thousands which equal to 26% of vehicles population in Manado. Mataram city located in the small island eastern of Bali, has 61.3 km^2 of administration area and 356141 populations. Passenger car population is 16763 cars or equal to 27% of vehicles population. Car population in Mataram is the lowest among 10 cities. Padang is the capital city of west Sumatera province which has 62.6 km2 of administration area and 0.8 millions populations. Passenger car population in Padang is 45 thousands or 15.5% of vehicles populations. The last city, Pontianak, the capital city of west Kalimantan province is located in the same island with Balikpapan. About five thousand people live in the city and administrative area cover 107.82 km2. Passenger car population in Pontianak is 26 thousands which equal to 8.3 % of total vehicles population. Comparing among cities in Indonesia, the highest PC ownership per 1000 persons found at Jakarta city around 200 units per 1000 persons. The lowest ones found at Makassar around 42 Passenger Car per 1000 persons (Figure 2).

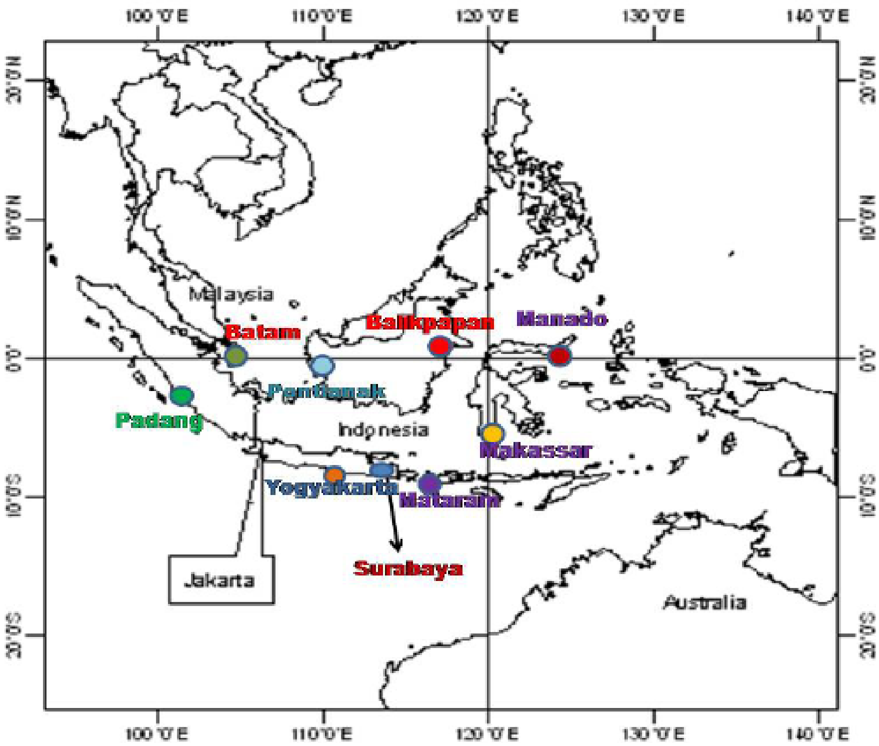

Figure 1 Locations of On-road Emission Measurements of Passenger car.

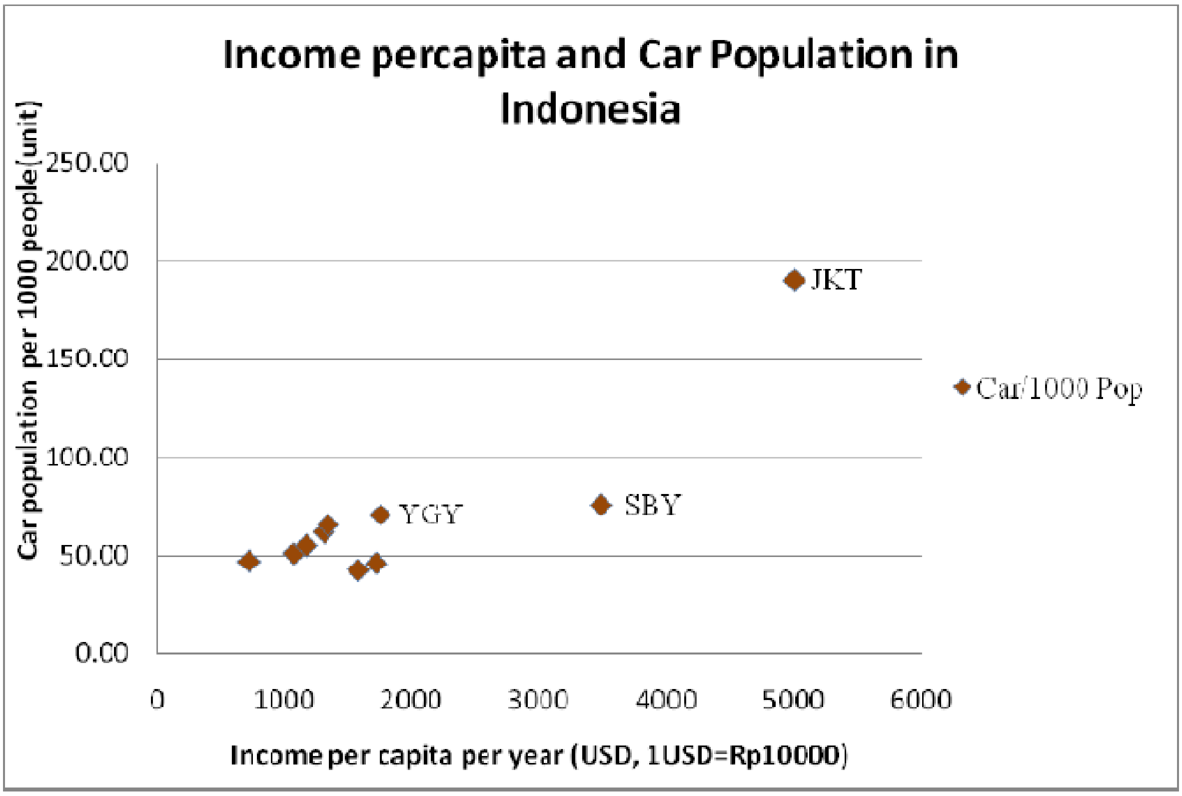

Figure 2. Car Population and Income per capita in Indonesia

Total sample sizes obtained from ten cities were 3697 data sets used in this study. About 441(11.93%) samples were taken from Jakarta, 192 (5.19%) samples from Yogyakarta, 99 (2.68%) samples from Surabaya, 263 (7.11%) samples from Balikpapan and 427 (11.55%) samples from Makassar, 765 (20.69%) samples measured at Batam, 354 (9.58%) samples from Manado, 355 (9.60%) samples from Mataram, 487 (13.17%) samples from Padang and 314 (8.49%) samples from Pontianak. Most of passenger car annual mobility in Indonesia is less than 10000 km per year (44.7%). About the engine size capacity of passenger car, 87.9 % respondents willing to owned cars with engine size capacity in between 1000 cc to 2000 cc and 53.7 % or samples are carburetor cars. Very good and good quality of car's maintenance found 47.3% samples were taken from 10 cities. Detail descriptive statistics of samples passenger car in this paper are shown in Table 2.

Table 2 Variable definition of Samples

Variable Name	Definitions	Total	Emission Test Failure		
			Fail_Test	Fail_CO	Fail_HC
	Samples (N)	3697	1129	983	314
CO	Carbon monoxide measured by the percent of total volume of emission gas	2.730 (2.975)	6.272 (2.719)	7.037 (1.921)	4.769 (3.89)
HC	Hydrocarbon measured by parts per million	488.60 (610.394)	1000.79 (864.726)	865.27 (790.021)	1597.73 (112.003)
ENGSZCLS	Engine Size classification by cubic centimeter displacement				
	(1) Engine Size ≤ 1000 cc	7.93%	53.92%	48.12%	14.33%
	(2) 1000< Engine Size ≤ 1500 cc	38.51%	34.67%	29.04%	11.53%
	(3) 1500< Engine Size ≤2000 cc	49.42%	25.42%	22.85%	5.64%
	(4) 2000 cc < Engine Size	4.14%	9.15%	7.84%	3.27%
RKTYRCLS	Running Kilometer per year				
	(1) RKTYR ≤ 10000 km/yr	44.68%	35.15%	30.61%	10.73%
	(2) 10000< RKTYR ≤ 20000	26.70%	25.56%	23.02%	5.38%
	(3) 20000< RKTYR ≤ 30000	14.11%	26.30%	22.46%	7.10%
	(4) 30000< RKTYR ≤ 40000	5.23%	33.68%	29.02%	9.84%
	(5) 40000< RKTYR ≤ 50000	3.47%	30.47%	28.13%	7.81%
	(6) 50000< RKTYR	5.82%	23.72%	19.53%	8.37%
I/M Quality	Air to fuel ratio(Lambda)				
Very Good	$0.95 \leq \lambda < 1.05$	38.42%	5.78%	4.58%	1.83%
Good	$0.9 \leq \lambda < 0.95$ & $1.05 \leq \lambda < 1.1$	18.95%	16.57%	14.00%	4.86%
Moderate	$0.85 \leq \lambda < 0.9$ & $1.1 \leq \lambda < 1.15$	13.51%	50.50%	47.09%	8.82%
Bad	$0.8 \leq \lambda < 0.85$ & $1.15 \leq \lambda < 1.2$	10.48%	76.49%	73.90%	12.14%
Very bad	$\lambda < 0.8$ & $1.2 \leq \lambda$	18.63%	55.67%	43.46%	23.69%

Two dependent variables for regression analysis are related to the passenger car exhaust emissions measurements of CO and HC. The dependent variables indicate emissions test failures of a passenger car, i.e., the passenger car emissions exceeds the levels designated in the standards. Table 2 show that emission levels of 30.5% samples are higher than allowable standard which means fails vehicle emission test.

4. MODEL ESTIMATIONS AND RESULTS DISCUSSION

The Bivariate Probit regression analysis is conducted using independent variables of engine size class, running kilometer per year of passenger car, engine fuel system (Carburetor), dummy variable maintenance quality, and sampling locations. In order to ascertain the influence of vehicles characteristics (engine size, running kilometer per year, carburetor, lambda) and the impact of city's characteristic (sampling locations) on passenger car emissions (i.e., CO and HC), two alternative specifications are estimated to test for the significance of inclusion of the factors. The first model *Model 1* includes the passenger car characteristics and we obtained the variables which determined significantly the emission test results. To analyze the influence of sampling locations, *Model 2* used to compare the probability of emission test among 10 cities.

Table 3 reports the estimation results of the regression analyses for both *Model 1* and *Model 2*. Looking at *Model 1*, all vehicle characteristics gives significant impact on CO and HC exhaust performance. Running Kilometer per year and engine size plays significant role in determining emission test failure for both CO and HC at any estimation results positively. In contrast, Engine fuel system (Carburetor) and Maintenance quality gives negative and significant in determining estimation results of CO and HC in all estimations. The probability to pass the exhaust emission test of passenger car with injection fuel system is increase compare to the carburetor ones. Basically, vehicle engine size (capacity) is directly related to emission and energy consumption. Vehicle with larger engine consume more fuel and emit more pollutions. There is often however a large difference between the most and least efficient vehicle within each engine size range *(17)*. Also, a large difference of engine pollution control device between engine size classes. In order to comply with the regulation, small size engine cars are worse compare to medium and large engine size cars. Observing all estimation results, dummy variable of maintenance quality keep remain stable as one of significant factor at 1% level which influence to the CO and HC emission test failure. One key parameter very effective in the formation of CO and HC is the air-to-fuel ratio when the fuel is burned *(18)*. In this study, air–to-fuel ratio (lambda) is taken as the *stoichiometric amount*. When air–to-fuel ratio is less than 1, it is impossible to burn all fuel as there is insufficient air. In this case, CO and HC should be emitted as products of incomplete combustion. Generally, air–to-fuel ratio is subject to passenger car maintenance conditions. Routine maintenance keeps air-to-fuel ratio near the *stoichiometric amount*, which automatically sustains the passenger car emissions at the desired levels. It was justified from observed samples that reducing the maintenance quality consequently increase the probability of emission test failure (Table 2).

Individual passenger car mobility per year (VKT per year) also play significant role in determining the probability of emission test failure. As private motorized mobility is based on vehicle kilometer travelled, which in turn is a surrogate for urban transportation emission, urban air quality is directly linked to urban structure *(11)*. As individual mobility by car, it was found in all cities that average individual mobility per year decrease gradually based on their vehicles age (Figure 3). Observed from samples, the highest average individual car mobility per year observed at Manado (27781 km/year) and the lowest one observed at Jakarta (14679 km/year). In contrast, Jakarta city leading for total private passenger car annual vehicle kilometer travelled at around 22,01x10[9] km follows by Surabaya at 5,3x10[9] km and the lowest one found at 0,38x10[9] km (Mataram). Considering annual vehicle kilometer travelled by passenger car per capita in the city level, lowest value 849 km/year estimated for Batam and the highest is around 2799 km/year for Jakarta city.

Table 3 Estimation results of Bivariate Probit Model for Passenger car in Indonesia

Variables	Bivariate Probit Model							
	Model-1				Model-2			
	CO		HC		CO		HC	
	Estimation	t-score	Estimation	t-score	Estimation	t-score	Estimation	t-score
ENGSZCLS	0.557	24.090	0.674	24.410	0.351	12.974	0.509	15.921
RKTYRCLS	0.133	7.606	0.133	6.290	0.092	4.945	0.115	4.673
CARB	-0.548	-10.20	-0.186	-2.344	-0.975	-12.41	-0.713	-4.931
I/M Class	-0.255	-16.823	-0.148	-7.473	-0.316	-17.942	-0.208	-9.600
City								
a. Jakarta					-	-	-	-
b. Surabaya					1.505	8.750	1.633	6.126
c. Yogyakarta					1.015	7.897	1.397	6.900
d. Balikpapan					1.085	8.774	1.227	5.822
e. Makassar					1.269	10.961	0.758	4.684
f. Batam					1.568	12.703	1.542	8.577
g. Manado					1.404	11.608	1.037	6.017
h. Mataram					1.089	8.998	1.395	8.214
i. Padang					1.283	11.015	1.512	8.857
j. Pontianak					0.949	7.373	1.053	6.113
RHO (F_CO,F_HC)	0.233				0.130			
Samples	3679				3679			
Log Likelihood	-2730. 481				-2475.107			

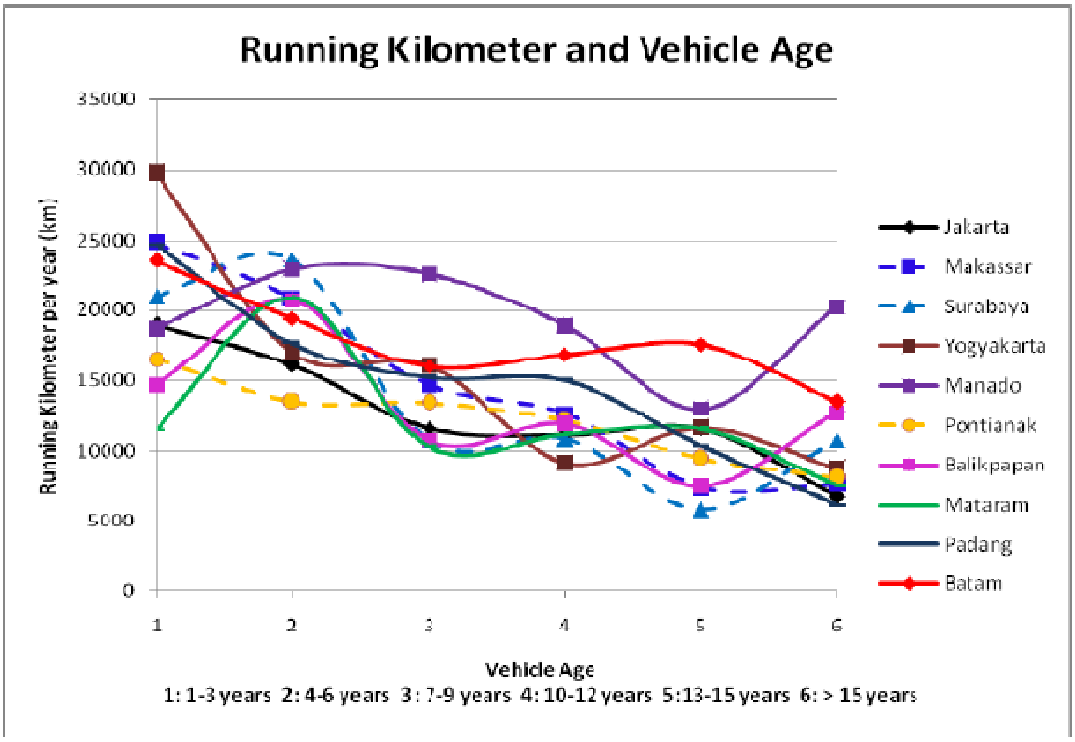

Figure 3 Running Kilometer and Vehicles Age

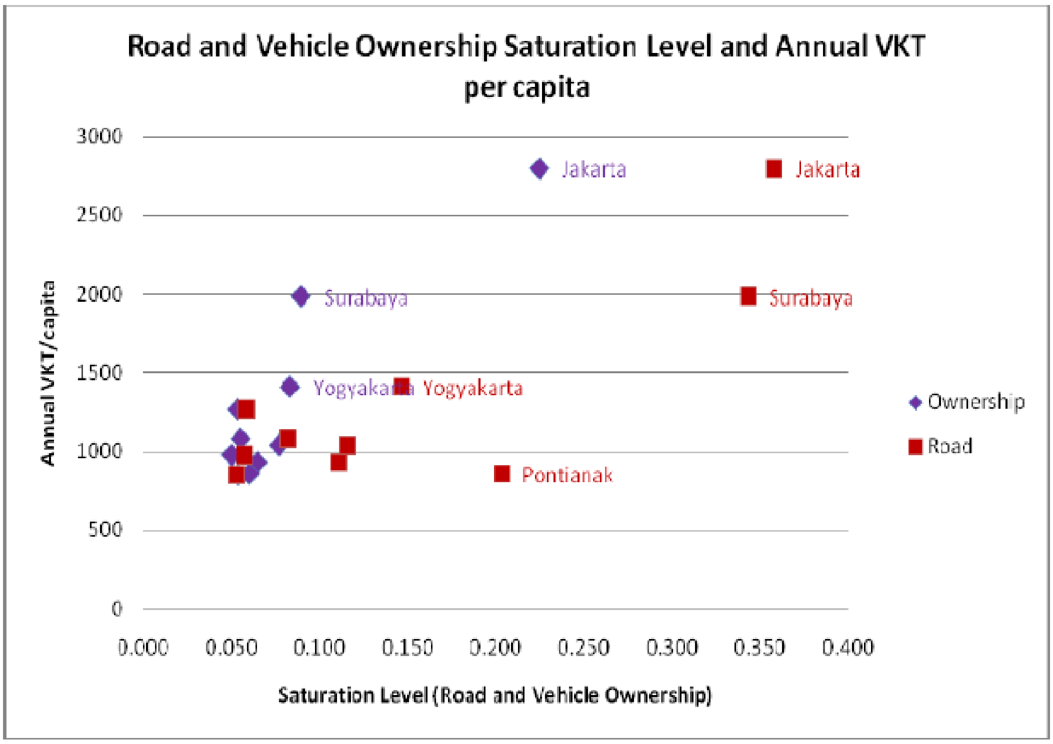

Figure 4 Passenger cars annual running kilometer per capita and urban indicators

The highest annual GDP per capita found in Jakarta 4992 $ (1$ equal to Rupiah 10.000,-) and the lowest found at Mataram 717 $ (Figure 2). Private vehicle road saturation level of the city calculated from 0.053 (Batam) to 0.358 (Jakarta) (Figure 4). The lowest private passenger car ownership saturation level accounted for Makassar (0.050) and the highest found at Jakarta (0.224) as shown in figure 4. Concerning to the four vehicles characteristics used in bivariate probit analysis, individual urban mobility (VKT) has linked and relationship with urban indicators at the city level. Based on the actual data for city level, the distribution data of road saturation level and vehicle ownership level of Jakarta city is differ compare to other eight cities. Surabaya's data located in between two groups (Jakarta and other 8 cities). In order to evaluate cause-effects relationship between vehicle running kilometer and urban city structure, we refer and modify previous study on VKT by Cameron *(11)*, Lyons (19) and Kenworthy *(20)*. Under dimensionless analysis, the simplest optimized form of a dimensionally homogeneous equation linking a city's private motorized mobility to a number of independent dimensionless ratios from the driver of its urban mobility is:

$$LN\_\Pi_{mob1} = p_0 + p_1(LN\_GDP) + p_2\,\Pi_{rds} \qquad (4)$$

Where urban mobility is restricted to private passenger vehicles as the only vehicle featuring in the data sets (10 cities), and p_0, p_1, and p_2 are optimal parameter from non-linear regression. Using the data at 2006/2007, the values of p_0 is 8.197(t-score: 3.415 and statistic P: 0.006), p_1 around 1.642 (t-score: 4.675 and statistic P: 0.000) and p_2 around 3.111 (t-score: 1.785 and statistic P: 0.074). Furthermore, considering Adjusted R_2 (0.915) this proposed simplest VKT's model for 10 cities in Indonesia statistically cannot be rejected.

In fact, we have two empirical situations which combine personal mobility and physical limitation caused by road saturation level in the city. First, lower mobility caused by high road saturation level observed in Jakarta city. Second, high mobility supported by low level of road saturation observed in other nine cities. If we assume that road saturation level could represent the congestion situation in each city, high congestion and low mobility found in Jakarta city. In contrast, high mobility supported by free-flow traffic situations observed in other nine cities. To measure influence of these two combinations on emission test failure, we modify our previous bivariate model which includes city sampling locations (*Model 2*). To do so, we use Jakarta's data as the reference and compare the probability of emission test result with other nine cities. We found positive values and differ significantly compare to Jakarta's data (Table 2). The probability to pass the emission test of vehicles in Yogyakarta, Surabaya, Balikpapan, Makassar, Batam, Manado, Mataram, Padang and Pontianak are increase significantly compare to passenger car in Jakarta city. Concretely speaking, the probability of passenger car pass the emission test is better for a high mobility in a free-flow situation rather than low mobility but congested city. And so, for I/M evaluation method at individual level, instead of vehicle running kilometer which represent personal vehicle mobility, we should taking into account another ‘unobserved’ parameter which reflect traffic situations. High congestion level cause more idle time and also more acceleration and deceleration. If this situation occurs frequently, empirical study confirmed that it will influence on vehicle emission performance. Due to the limitation data, this conclusion made only for the city level. It is necessary to observe more detail about linked or relationship between emission test failure and their daily travel situations (origin-destination, route choice, departure time, and traffic flow) in the next near future research.

5. CONCLUSIONS AND FUTURE RESEACH ISSUES

In this study, bivariate probit regression model applied to examine the probability emission test failure of passenger car as part of the inspection and maintenance program at ten cities in Indonesia which are Jakarta, Yogyakarta, Surabaya, Balikpapan, Makassar, Batam, Manado, Mataram, Padang and Pontianak. We successfully identified the characteristic of passenger car which affect significantly on emission test failure of Carbon Monoxide and Hydrocarbon. As a preliminary assessment of the inspection and maintenance program for in-use vehicles in Indonesia, this study indicates that vehicles running kilometer per year, fuel system injection, engine size capacity and air-to-fuel ratio play a significant role in determining I/M test results. In terms of citizen responsibility or their urban lifestyle toward low carbon society, passenger car owners should be fully responsible to do regular and routine maintenance and repair in order to reduce their passenger car emissions. GDP per capita and urban road saturation level of city has non-linear relationships with average passenger car running kilometer per year as estimated by using dimensionless analysis of data obtained from ten cities in Indonesia. Related to the urban city situations, the probability of passenger car pass the emission test is better for a high mobility in a free-flow situation rather than low mobility but congested city. Empirical study confirm that emission cars measured at Surabaya, Yogyakarta, Balikpapan, Makassar, Batam, Manado, Mataram, Padang and Pontianak are significantly less to fail on vehicle emission test compare to Jakarta’s car. In order to perform cross-sectional analysis of Inspection and Maintenance program among cities under Adipura program in Indonesia, we should consider other parameter represent real traffic situations of the city which difficult to obtained from vehicle characteristics.

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