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EDITORIAL

This (double) issue of the REAAA Journal (Volume 16, Nos 1 and 2) contains six papers.

- ❑ Construction of Sungai Prai Bridge, Butterworth, Penang, by Ir Dr Ismail Bin Mohamed Taib, Public Works Department, Malaysia and Ir Tan Yang Peng, Perunding Jurutera DAH Sdn Bhd, Malaysia

The Sungai Prai Bridge was the most complex and challenging part of the 12.1 km long Butterworth Outer Ring Road project. The bridge links the port of Butterworth to the primary arterial North-South Highway and to the Penang Bridge. It fulfils a role taking heavy traffic, particularly port traffic away from the congested mixed use and residential areas of Butterworth and Prai. This paper describes the project, the alternative designs considered and the implementation of the project.

- ❑ Impact of Motorcycle Travel Behaviour on Saturation Flow Rates at Signalised Intersections in Malaysia, by LV Leong, Universiti Sains Malaysia, WH Wan Ibrahim, Universiti Malaysia Sarawak and AF Mohd. Sadullah, Malaysian Institute of Road Safety Research (MIROS)

In Malaysia, almost half of the registered vehicles are motorcycles and motorcycle ownership has increased significantly, from 0.17 motorcycles per person in 1990 to 0.29 in 2007. The improper treatment of motorcycles when signalised intersections are designed results in additional traffic congestion and may increase the number of motorcycle accidents. In this study, the behaviour of motorcyclists at signalised intersections in Malaysia, and their influence on estimates of saturation flow rates, was examined and a model that includes their behaviour when estimating saturation flow rates developed.

- ❑ Environment and Road Safety in Malaysia, by Jamilah Mohd Marjan, Malaysian Institute of Road Safety Research (MIROS)

There are approximately 6,000 fatalities in Malaysia annually, or 3.7 deaths per 10,000 registered vehicles. The Government of Malaysia has set a target of 2 deaths per 10,000 registered vehicles by 2010. Malaysia uses the integrated planning matrix where the emphasis in safety initiatives is focused on human, vehicle and environment factors, at both the pre-crash, crash and post-crash stages. The road environment initiatives are described in this paper.

- ❑ Road Fund: A Tool For Asset Preservation In Bangladesh, by Misbah Uddin Khan, Chobe District Council, Botswana and Shamima Nargis, Farhana Husna, Sheikh Sohel Ahmed and Mohammad Bulbul Hossain, Roads and Highways Department (RHD), Bangladesh

The Roads and Highways Department (RHD) of Bangladesh has a sound pavement management system (PMS), which consists of data collection, a road database and use of the Highway Development and Management (HDM-4) model for asset preservation. However, RHD's backlog is increasing regularly due to its assets not being maintained on time owing to a lack of sufficient funding. In this paper, relevant Government policies in the transport sector and the new Road Master Plan, directed especially on maintenance, are reviewed. It is concluded that increased road funding would be the long-term solution for road network management in Bangladesh.

- ❑ The Development of an Accident Black Spot Program in Singapore, by Hau Lay Peng and Ho Seng Tim, Land Transport Authority, Singapore

A black spot program (BSP) is a road safety engineering strategy that uses pre-defined criteria and targets to identify and treat accident-prone locations. Singapore's BSP was commissioned in 2005, after years of preparatory work. Most developed countries have defined their own black spot criteria and developed their own strategies based on their individual traffic and accident histories. This is a vital step if a cost-effective reduction in highway accidents is to be achieved. The purpose of this paper is to discuss the Singapore BSP and to present some initial findings.

- Development of a Decay Curve for Pavement Marking Retroreflectivity, by Hyun-Suk Lee and Heung-Un Oh, Korea Expressway Corporation

The performance of retroreflectivity varies according to traffic volume age, the type of pavement marking material and its colour. Data collected on freeways throughout Korea was used to develop regression equations relating traffic volume and service life as independent variables and retroreflectivity as the dependent variables. This paper presents the results of the study, including a literature review of previous work in this area. It is recommended that aspects of pavement marking performance other than retroreflectivity, such as wear and adhesion to the pavement surface, also be considered when determining if a linemaking should be replaced.

The Editorial Panel continues to seek papers and technical notes for publication in the Journal. The membership of the Editorial Panel follows. The Panel is striving to publish at least one paper from each Chapter or region each year. Authors wishing to submit papers should contact: journal@arrb.com.au or kieran.sharp@arrb.com.au. Readers who would like to nominate for membership of the Editorial Panel should contact their appropriate Chapter.

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Construction of Sungai Prai Bridge, Butterworth, Penang^{*}

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ABSTRACT

The Sungai Prai Bridge was the most complex and challenging part of the 12.1 km long Butterworth Outer Ring Road project. The bridge links the port of Butterworth to the primary arterial North-South Highway and to the Penang Bridge. It fulfils a role taking heavy traffic, particularly port traffic away from the congested mixed use and residential areas of Butterworth and Prai. This paper describes the project, the alternative designs considered and the implementation of the project. The success of the bridge over Sungai Prai attests to the importance of a fully integrated approach from structural conception to construction to achieve an economical, efficient design, and an environmentally friendly and aesthetically pleasing structure. The adoption of extensive precast segmental and special construction techniques was the key to the delivery of the project.

1 Introduction

Situated on the west coast of Peninsular Malaysia, the town of Butterworth is one of the country's largest port complexes. The Sungai Prai Bridge was the most complex and challenging part of the 12.1 km long Butterworth Outer Ring Road project. The bridge links the port of Butterworth to the primary arterial North-South Highway and to the Penang Bridge. It fulfils a role taking heavy traffic, particularly port traffic away from the congested mixed use and residential areas of Butterworth and Prai. This paper describes the project, the alternative designs considered and the implementation of the project.

2 Project Description

The project was a design and build contract awarded to Lingaran Luar Butterworth (Penang) Sdn. Bhd. It formed part of the Butterworth Outer Ring Road (BORR) project.

The Sungai Prai Bridge is approximately 1.4 km long plus about 1.25 km of ramps attached to the western approaches. The main line is a dual three-lane elevated section comprising the eastern approaches, 400 m long, and the western approaches, 450 m long, and the main bridge across Sungai Prai (485 m long). The dual three-lane road is 28.8 m wide on the main bridge and 27.8 m wide on the approaches. The ramps are 9.8 m wide. The plan, elevation and cross-section of the bridge are shown in Figure 1 and Figure 2.

3 Alternative Design

The original design of the project involved a variety of bridge types and forms including precast beams and cast in situ post-tensioned box girders for ramps and approach viaducts, and cast in situ balanced cantilever construction for the main river bridge. The main bridge has a central span of 85 m and two side spans of 50 m.

^{*} This paper won an award at the 7th Malaysian Road Conference, 17-19 July 2007.

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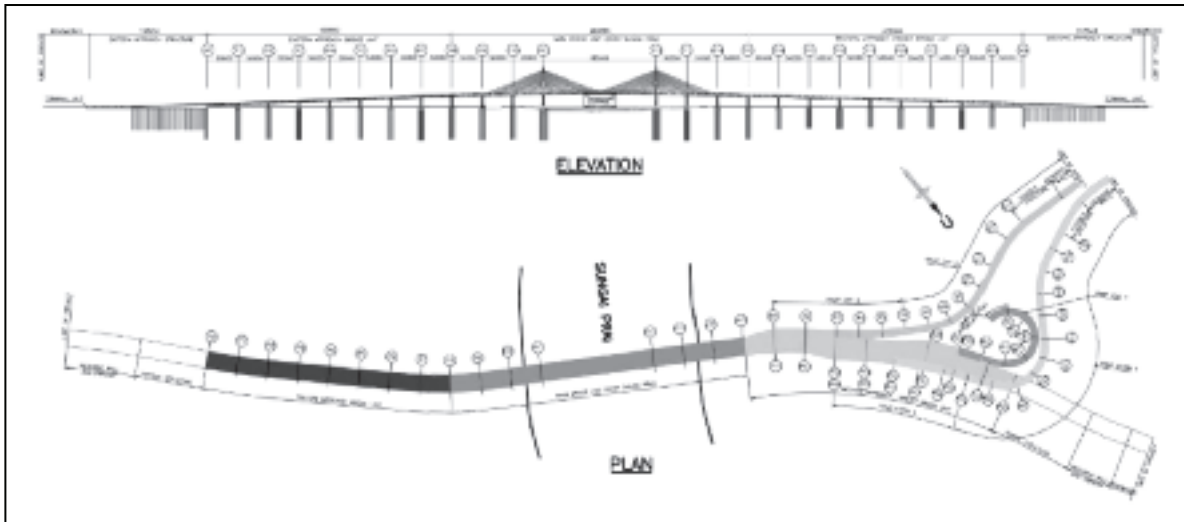


Figure 1: Plan and elevation of Sungai Prai Bridge

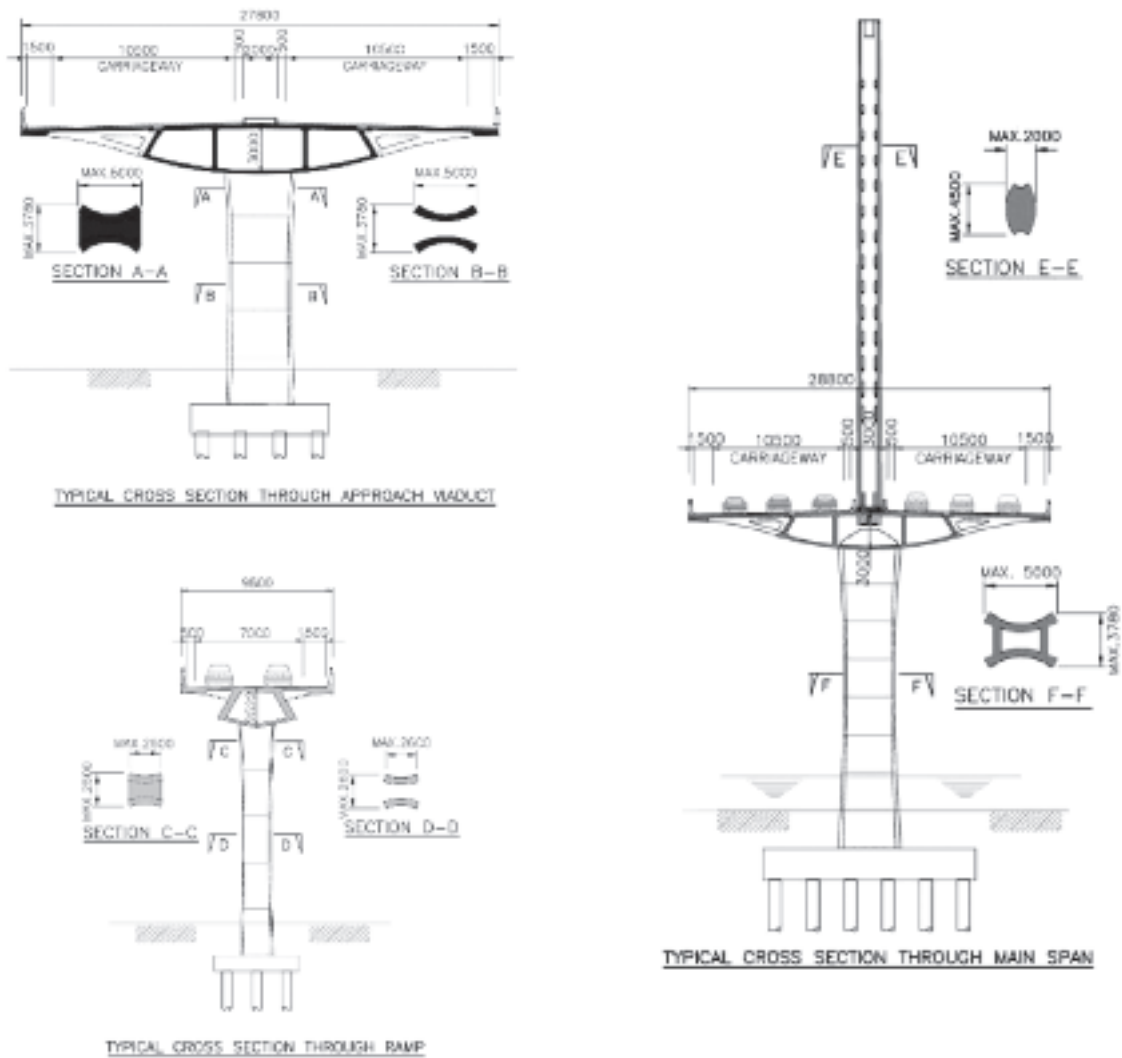


Figure 2: Cross-section of Sungai Prai Bridge

The main features of the alternative design were:

- ❑ deleting the two piers in the middle of the river resulted in an increase in the river span to 185 m
- ❑ bridge concept changed from in situ balanced cantilever construction to precast segmental construction
- ❑ twin deck with two lines of supports changed to a single deck with a single line of support
- ❑ pier cross-heads eliminated
- ❑ raked piles eliminated
- ❑ provisions for durability design included.

By increasing the navigation span of the river crossing, the piers are located in shallow water and clear of the shipping lane. This eliminates the need to check the river piers for ship impact or to provide some form of protective system. The river crossing is now a cable stay bridge which provides a focal point for the elevated highway, local environs and shipping. The desired bridge aesthetic was thereby achieved.

The shape of the piers was rationalized such that a single master pier form was used for the construction of all piers. They were of a geometric form that not only enhances their visual quality but also facilitates construction by slip forming.

The decks were precast in a purpose-made yard using match casting techniques. This allowed work to proceed during inclement weather. Precasting in a controlled environment promotes good workmanship, good curing and good finish which was obviously one of the design objectives.

The bridge deck for the main cable stay bridge and approach viaducts was constructed in two stages. The first stage involved the construction of a central spine box. In the second stage, a pair of side frames was attached to the central spine box girder using the spine box girder for their delivery. This method of construction reduced the weight of precast segments, thus reducing equipment costs.

Photos of the construction are shown in Figure 3 and Figure 4.



Figure 3: Adjusting pier head segments before lifting



Figure 4: Steel bracket supported the pier head segments

4 Construction of Approach Viaducts

The deck girders of both the eastern and western approach viaducts were designed for glued, match-cast, precast concrete spine segments using a continuous span-by-span construction technique. During the gluing and stressing phase, the segments were fully supported from above using a purpose-built 'launching gantry' which was also able to be launched from one span to the next upon completion of each span. The girders were prestressed by internal prestressing. The cables were coupled at the each phase of construction to provide a continuous draped cable system.

The 880 tonne launching gantry (see Figure 5) was designed to allow for the following conditions:

- suspension of the segments weight of 1500 tonne for complete 50 m long span
- lifting of 150 tonne segment
- segment can be delivered from the deck or from the ground
- positioning of the pier segments
- self-launching operation to the next pier
- erection of cantilever segments ahead of the front support

The overhead launching consists of the following:

- two steel box girders 120 m long and 3.5 m high
- two main supports, each equipped with four 500 tonne hydraulic supports
- a winch trolley with a lifting capacity of 150 tonne and 400 m of cable

The launching operation was performed by lifting the segments one by one and hanging them to the box girders by means of high tensile steel bars. In order to deliver the segments from the rear of the launcher, the segments were lifted and moved between the box girders above the main supports. Thus, the cantilever segments can be brought to their final positions ahead of the front support.

The segments were then glued together permanently using high tensile prestressed steel bars. Once the alignment was found satisfactory, the span was stitched and the prestressing tendons installed. The coupling of the tendons with the previous span was provided only at the CSC segment. The webs of this segment were partially cast which allowed positioning of the couplers of the internal prestressing. After installing the couplers, the webs were cast before the prestressing force could be applied.



Figure 5: Overview of 880 tonne overhead launching gantry (1500 tonne capacity)

5 Construction of Main Span Cable Stayed Bridge

The main span cable stayed bridge comprises a central span of 185 m with three balancing spans, 50 m long, on either side. The bridge deck consists of a triple-cell box spine girder with side frames. The deck of the main span is picked up along its median by a plane of cable stays running to a concrete tower also located in the median. The stays pass through the tower via saddles to be anchored in the median area of the approach viaducts on either side. The stay cables support the deck at every other segment and are anchored in blocks at the deck level. They consist of continuously extruded galvanised strands, 15.7 mm in diameter, waxed and coated with high density polyethylene. The cable strands vary in number from 15 nearest the tower to 54 nearest the mid-span.

The main span cantilever deck was built outwards from the pier by progressive cantilevering using a purpose-built 'A Frame'. The typical cycle of the main span segment construction was as follows:

- erection in cantilever of two segments
- launching of the 'A Frame'
- installation of the stay cables.

Each segment is 3.158 m long and 70 tonne in weight (standard segment) and 100 tonne (segment with stay anchorages).

As the water level in the Sungai Prai during low tide is very low, the idea of delivering the segments under the bridge with a barge was quickly supplanted in favour of delivering the segments from the deck at the back of 'A Frame'. Due to the central plane of stay cables, the segments must be delivered on one side of the deck centreline and the frame and its equipment had to be designed to accommodate this. The travelling beam installed at the mid-height of the frame was equipped with hydraulic jacks which allow transverse motion of the segment once the stay cables have been cleared. The key component of the frame was its 130 tonne capacity hydraulic jack to pick up the segment from the trailer and lower it in front of the tip of the cantilever section (Figure 6). After two segments had been erected, the frame was pushed to its next position onto the launching rails by means of long-stroke hydraulic jacks.



Figure 6: Lifting of cable stay segment using 'A Frame'



Figure 7: Stressing of stay cable strands using monostrand jack

The stays were installed using the Freyssinet iso-tension system of 'strand by strand' installation. The outer sheath was assembled on the deck by welding together standard lengths of sheathing. The first strand was installed and lifted into position with the sheathing. It was then stressed to a predetermined force and attached to the stressing anchorage with a special device incorporating a load cell. The second strand was installed, connected to the anchorages and stressed using a monostrand jack (Figure 7). A second load cell recorded the force in the second strand, which was stressed until the forces in the two strands were equal. The process was repeated until all the strands were installed in the stay.

6 Construction of Ramps and Bifurcations

There are three ramps: exit ramp 1 (total length 272 m), exit ramp 2 (total length 527 m), and entry ramp 1 (total length 503.6 m). The superstructure for the ramps consists of a single cell box girder 9.8 m wide and 2.522 m deep. The cross-section of the ramps was derived entirely from the main approach viaduct forms in such a way that all the ramp/viaduct junctions provide a logical and elegant transition from one to the other. The deck girder of the ramps was designed to be built with glued, match-cast, precast concrete spine segments using a continuous span-by-span construction in the same manner as the viaducts. The prestressing is also similar. However, due to the lesser width, the section was designed to be cast in one piece.

Due to the very tight radius (43 m) for ramp spans and the complex bifurcations, where the ramp merges with the main line must be erected and prestressed in single operation, the following methods were used to build the ramps and bifurcations:

- a 'small' launching gantry
- heavy duty falsework
- combination of launching gantry and heavy duty falsework.

The 400 tonne 'small' overhead launching consisted of two steel box girders 112 m long and 2.5 m high (Figure 8). Two rails welded to the bottom flange of each beam ran onto the rollers during the launching operation. The winch trolley travelled on two rails welded to the top flange of the girders. The launching gantry was equipped with a 60 tonne self-braking winch housed in a trolley that ran onto the rails on the top flange of the rail beams. Four hydraulic motors, mounted at the ends of the trolley, moved the winch trolley along the rail beams as well as to launch the gantry.



Figure 8: View of 400 tonne small launching gantry for erection of ramps

The launching operation cycle commenced when the last span had been prestressed and released from the beams. The gantry was then launched to the next span. The third support had to be placed and properly adjusted onto the next pier segments. In the case of the pier with bearings, the segments were rested onto a temporary steel support clamped to the pier head. This support was designed to sustain the load from the launcher and the span erected.

Lifting of the segments was carried out with the 60 tonne winch trolley. The winch travelled on top of the beams from one end to the other so that the cantilever segments over the front support could be lifted. Once all the segments were lifted, they were glued and temporary prestressed by means of high tensile steel bars. Alignment control was carried out continuously during gluing to ensure that the span matched the cantilever of the previous span. Once the satisfactory alignment was achieved, the construction joints were stitched and the prestressed tendons threaded and stressed. The construction cycle achieved with this method was ten days for a typical 40 m span.

Owing to the very tight radius (down to 43 m) of the ramp spans and the bifurcation spans where the simultaneous use of two launching gantries was not possible, heavy duty falsework was used to erect these structures (Figure 9).

The falsework was made of heavy duty shoring towers supporting custom-built steel carriages allowing adjustment of the concrete segments in the three dimensions by means of hydraulic or screw jacks. The four individual towers were made of modular elements in order to adapt to the height of the span it supported. These individual towers were braced longitudinally (2 or 3 modules together) to ensure stability during initial assembly and to facilitate the removal and repositioning for the next span. Pier segments towers were fixed to the pier by two inserts cast in the lateral faces of the pier head. Lateral walkways were provided on both sides at the top of the towers and individual sliding beams equipped with stainless steel on their top flange were bolted to the soldier top end-plates. The sliding beams were set horizontally and designed to allow ± 300 mm displacement of the segments in both the longitudinal and transverse directions for adjustment purposes.

Each segment was placed on a sliding carriage comprised of a horizontal frame equipped with four sliding plates and three or four adjustable mobile columns. Vertical adjustment was achieved by acting on the 50 tonne capacity hydraulic jacks placed under the mobile columns. The load was secured mechanically using four screw jacks at the base of each mobile column. Horizontal adjustment was conducted using simple screw jacks fixed to the sliding beams. A 200 tonne mobile crane was used to lift all the segments with a steel spreader beam clamped onto top slab of the segments by high tensile prestressed steel bars. The operation of segment gluing, construction joint stitching and prestressing was quite similar to the spans erected with a launcher. However, great care was taken to align the segments since adjustment of the entire span before stitching of the construction joints was a delicate operation.



Figure 9: Construction of bifurcation using combination of launching gantry and heavy duty falsework

7 Installation of Side Frames

The side frames were installed after the main spine segments had been erected using cranes placed either on the completed deck or on the ground wherever access was made possible. The weight of the side frame is approximately 35 tonne; it consists of two vertical ribs and a slab about 6 m long and 8 m wide.

Using a crane, the side frames were slowly lowered onto two nibs purposely designed on the external faces of the outer webs of the spine segments (Figure 10). These small nibs supported the vertical load of the side frames but the titling of the large concrete panels was sustained by the additional temporary devices clamped onto the top slab of spine segment (Figure 11). These temporary devices consisted of steel brackets plugged into the top slab of the segment; they were able to receive high tensile steel bars connected to the side frame. For each side frame, eight bars were stressed to 12 tonne, resulting to an average of 100 tonne horizontal force per side frame.



Figure 10: Lifting of side frame using mobile crane



Figure 11: Temporary clamping devices for side frame

8 Conclusion

A general view of the completed bridge is shown in Figure 12. The success of the bridge over Sungai Prai attests to the importance of a fully integrated approach from structural conception to construction to achieve an economical, efficient design, and an environmentally friendly and aesthetically pleasing structure. The adoption of extensive precast segmental and special construction techniques was the key to delivery of the project. In November 2006, the Sungai Prai Bridge won two IStructE (Institution of Structural Engineers) Structural Awards 06 for *Supreme Award for Engineering Excellence* and *Transportation Structures Award*.



General view of Sungai Prai Bridge



General view of ramp

Figure 12: General views of Sungai Prai Bridge

Impact of Motorcycle Travel Behaviour on Saturation Flow Rates at Signalised Intersections in Malaysia

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ABSTRACT

Saturation flow rate is an important parameter for capacity and operational analysis of signalised intersections. Saturation flows estimated using the US Highway Capacity Manual 2000 (US HCM 2000) cannot be used directly in many developing countries due to the heterogeneity of traffic composition, especially when motorcycles are a major form of transportation. In Malaysia, almost half of the registered vehicles are motorcycles and motorcycle ownership has increased significantly, from 0.17 motorcycles per person in 1990 to 0.29 in 2007. The improper treatment of motorcycles when signalised intersections are designed results in additional traffic congestion and may increase the number of motorcycle accidents. Studies of motorcyclist behaviour at signalised intersections are needed to help with the design of signalised intersections, to increase the level of service at signalised intersections and to reduce congestion and the number of accidents involving motorcycles. In this study, the behaviour of motorcyclists at signalised intersections in Malaysia, and their influence on estimates of saturation flow rates, was examined and a model that includes their behaviour when estimating saturation flow rates developed. Subsequently, comparisons of saturation flow rates estimated by using the US HCM 2000 and the Malaysian Arahan Teknik (Jalan) 13/87 showed significant differences.

1 Introduction

Signalised intersections play an important role in the performance of arterial roads, particularly in urban areas where signalised intersections can be the main sources of traffic congestion and traffic accidents (Minh and Kazushi 2003). The method currently used to estimate saturation flow in Malaysia (Arahan Teknik (Jalan) 13/87 – Ministry of Works Malaysia 1987), was based on the method developed by Webster and Cobbe (1966) in the United Kingdom in the 1950s and 1960s in which the behaviour of motorcyclists was not taken into consideration.

More recently Malaysian authorities have been using the US Highway Capacity Manual 2000 (US HCM 2000) (Transportation Research Board (TRB), 2000) to design and analyse signalised intersections. Due to differences in the road system, urban travel behaviour, and the mix of vehicle composition in Malaysia compared to the dual categories of vehicles, i.e. light and heavy vehicles, used in the US, the application of this Manual may not be the best choice for analysing local traffic conditions in Malaysia. In Malaysia, registered vehicles include passenger cars, motorcycles, buses and medium and heavy lorries, but almost 50% of the registered vehicles are motorcycles.

Whilst significant work has been conducted to improve the understanding of the effects of mixed traffic on the capacity of signalised intersections, only limited research has considered the unique characteristics of motorcycles. Cuddon and Odgen (1992) grouped motorcycles travelling within a

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lane (not between lanes) with passenger cars, whereas Stokes (1989) concluded that motorcycles and bicycles had little effect on saturation flow. Branston and van Zuylen (1978) suggested that unless the proportion of motorcycles or bicycles in the traffic stream was >20%, they had very little effect on saturation flow and could be ignored for practical purposes. In Vietnam, Nguyen and Montgomery (2007) introduced a new methodology to study the variation of saturation flow and vehicle equivalence factors. In the study, a 'motorcycle equivalent unit' (MUC) was used instead of the conventional 'passenger car equivalent' (PCU) to take into account the effect of mixed traffic dominated by motorcycles. Five regression models were derived to describe the variation of saturation flow in three traffic compositions and two methods of counting. They also estimated the MCU values for different vehicle types making different turning movements.

A study was also conducted in Thailand (Rongviriyapanich and Suppatrakul 2005) to investigate the effects of motorcycles at signalised intersections and the mid-block of urban streets. Based on the findings of their research, they recommended that a special area for motorcycles in front of the stop line of a signalized intersection should be provided to accommodate the high number of motorcycles on the road. They also found that the effects of motorcycles at mid-block varied considerably with flow rate and vehicle composition. In Taiwan, the segregated traffic flow concept was promoted and successfully implemented to improve the performance of traffic which included motorcycles. Segregation in Taiwan takes the form of two-stage left-turn regulation for left-turn motorcycles and the head start holding zone for motorcycles (Hsu 2006).

The impact of motorcycles in Malaysia should not be ignored because they are common vehicle type. The number of motorcycles registered in Malaysia in 2007 was 7.9 million, or approximately 47% of the total number of vehicles registered in the country (Ministry of Works Malaysia 2008). Even though Malaysia has a higher percentage of motorcycles than other western countries, the treatment of motorcycles in Malaysia is simplistic and effective estimates of saturation flow cannot be obtained. The objective of this study was to incorporate motorcyclists' travel behaviour into the formulation for estimating saturation flow. In-depth studies of motorcyclists at signalised intersections were conducted to determine their behaviour and this information was taken into account in the formulation of saturation flow rates and the performance of signalised intersections.

2 Background

The most common type of motorcycles in Malaysia has a small engine capacity (<250 cc). Motorcyclists can traverse a signalised intersection in three different ways:

- The motorcyclist may use the lateral gaps between larger vehicles to weave in and out of the traffic stream to reach the front of the queue while the signal is red. Due to the large number of motorcycles, most stop beyond the stop line. These motorcycles are grouped as one type.
- Most approach lanes at signalised intersections in Malaysia are wide enough to allow motorcyclists to travel alongside other vehicles while they traverse the intersection.
- Motorcyclists follow other vehicles in a structured manner.

The behaviour of motorcyclists at an intersection was divided into those within the flow and those outside the flow. Motorcycles within the flow follow a first-in-first-out rule, implying that they travel either in front of, or behind, other vehicles in the traffic stream. Motorcycles outside the flow are those that do not follow the first-in-first-out rule. This second category consists of motorcycles stopping in front of the stop line during the red signal and those that eventually cross the intersection beside other vehicles in a single approach lane. Based on research in the Rama 4 area of Bangkok (Montgomery and May 1986), motorcycles crossing the stop line during the first 6 second of effective green time (including the motorcycles stopping beyond the stop line) had no effect on traffic flow. Therefore, motorcycles travelling through the intersection during the first 6 seconds of the green cycle were categorised as motorcycles outside the flow.

Only the motorcycles within the flow have an impact on traffic flow since these motorcycles follow the first-in-first-out rule. These are the only vehicles considered in the analysis and design of signalised intersections (Papacostas 1987).

3 Study Approach

In this study, data on motorcycle travel behaviour was collected by using audio cassette recorder at signalised intersections in both the Central Business District (CBD) and non-CBD areas. Motorcycles were segregated into two categories:

- motorcycles outside the flow, m_o
 - motorcycles that stopped beyond the stop line
 - motorcycles crossing the stop line during the first 6 seconds of the green light period (excluding motorcycles beyond the stop line)
 - motorcycles travelling alongside other vehicles
- Motorcycles following other vehicles in a structured manner or motorcycles within the traffic flow, M_f .

Hsu et al. (2003) found that motorcycles normally travel on the side-lane of a street. Therefore, lane position data were collected and used in model development. The lane positions considered were:

- nearside lane (nearest to the curb)
- central lane
- offside lane

Initially, an independent-sample t-test was conducted to evaluate the effects of area type on the segregation of motorcycles and an analysis of variance was conducted to substantiate the effects of lane position on the behaviour of motorcyclists at signalised intersections.

Vehicle discharge patterns during the 'green time' were also collected with audio cassette recorders to help determine the saturation flow rate. The term 'green time' refers to the 'green plus amber' period. Data were collected for an average of 30 signal cycles. By observing vehicle discharge patterns, the number of vehicles discharging from a queue in successive 6 second intervals was determined. This method is commonly used to compute saturation flow. In the analysis, only saturated intervals were considered. The flow for each saturated interval, except the first and the last interval was averaged and the saturation flow calculated using the method described in Road Research Laboratory (1963).

4 Data Collection

Traffic flow data were collected in CBD and non-CBD areas under dry-weather conditions for through traffic with a level gradient in several major Malaysian cities. The through-only lanes reflected an ideal situation with no interference due to cars, taxis or buses picking up and setting down passengers, commercial vehicles loading or unloading goods and no parking activity in the adjacent lane. The sites selected had different geometric conditions such as lane width, approach grade and the position of the straight-through traffic lanes (nearside or non-nearside). The signalised intersections studied were either fully saturated or had adequately saturated portions of the green interval of longer than 20 seconds (Brown and Ogden 1988).

As discussed earlier, data were collected by observing vehicle discharge patterns using audio cassette recorders. These were used because the time headway between successive vehicles had to be measured and observers otherwise might not have enough time to record the actual time headway for each vehicle passing through the stop line (Brown and Ogden 1988; Teply and Jones 1994; William Lam 1994). By using a cassette recorder, events in the observed lane such as the beginning of the green interval, the passage of the rear axle of each passing vehicle over the stop line, vehicle type, the end of saturation flow and the beginning of the amber and red intervals could be noted. The number of motorcycles stopped in front of the stop line during the red cycle and the number of motorcycles travelling alongside other vehicles during the green cycle were also recorded. This process was repeated for subsequent green cycles. Data was not collected if vehicles travelled through the intersection during the red cycle.

The vehicle types distinguished in the study were:

Class 1: passenger cars, including taxis, small vans and utilities

Class 2: lorries with two axles and mini buses

Class 3: trailers with more than two axles

Class 4: buses

Class 5: motorcycles

Data was collected during peak periods (morning peak: 7.30-9.30 am, afternoon peak: 12.00-2.00 pm or evening peak: 4.30-6.30 pm) on weekdays when traffic flows at the intersections were typical, but saturated. Traffic flow data was collected at 56 signalised intersections in various states throughout Malaysia. For each signalised intersection, traffic flow data was collected simultaneously from several approach lanes that satisfied the predetermined conditions. Traffic flow data was collected for a total of 64 single lane streams. Details of the sites are given in Table 1. For any single lane, data was collected for an average of 30 signal cycles. Saturation flow rates computed for each of the 64 lanes based on the observed vehicle discharge data were compared with the saturation flow rates estimated from using the US HCM 2000, Arahan Teknik (Jalan) 13/87, and the results obtained in this study.

5 Analysis of Motorcycle Travel Behaviour

Initially, independent-samples t-testing was conducted to check the influence of area type on motorcycle behaviour. This was done to justify the need for incorporating an area-type dummy variable in the model. One-way analysis of variance (ANOVA) was then conducted to check the effect of lane position on the behaviour of motorcycles at signalised intersections. Two-way ANOVA was then conducted to check for interaction between the two factors.

5.1 Independent-samples t-test

In order to select the appropriate t-test (equal or unequal variance), the Levene test for equality of variances was used to test whether the two samples had statistically equivalent variances. Pooled-variance t-testing was conducted if the population variances for the two groups were equal (i.e. the distributions had the same shape) while separate-variance t-testing was used if the population variances for the two groups were not equal. A 95% confidence interval was used in the Levene test. The results obtained from the Levene's testing showed that the variances of motorcycles within flow between the CBD and non-CBD sites were equal. As a result, the pooled-variance t-test was used in the next stage of the analysis and the results shown in Table 2.

Based on the observed significant level of 0.001 in Table 2, the null hypothesis was rejected. It can be concluded that the mean values for motorcycles within flow between the CBD and non-CBD areas were significantly different. Therefore, the area-type dummy variable needed to be included in the model in order to take into account the effect of area type on motorcycle behaviour.

Table 1: Details of Data Collection Sites

Site No.	Lane Name	Lane Width (m)	Gradient	Site No.	Lane Name	Lane Width (m)	Gradient
Area: CBD							
1	Gama 1	3.2	level	17	Medan Tuanku 1-1	3.3	level
2	Gama 2	3.3	level	18	Medan Tuanku 1-2	3.3	level
3	Jln Ampang 1	3.1	level	19	Medan Tuanku 1-3	3.3	level
4	Jln Ampang 2	3.2	level	20	Medan Tuanku 1-4	3.3	level
5	Jln Leong Boon Swee 1	3.8	level	21	Medan Tuanku 1-5	3.3	level
6	Jln Pahang 1	3.6	level	22	Medan Tuanku 1-6	3.3	level
7	Jln Pahang 2	3.6	level	23	Medan Tuanku 1-7	3.3	level
8	Jln Raja Musa Aziz 2	3.8	level	24	Medan Tuanku 1-9	3.3	level
9	Jln SAS-Ipoh 2	3.1	level	25	Medan Tuanku 2-1	3.5	level
10	Jln Sultan Iskandar 2-1	3.0	level	26	Medan Tuanku 2-2	3.5	level
11	Jln Tun Perak 1	3.6	level	27	Medan Tuanku 2-3	3.5	level
12	Komtar 1	3.0	level	28	Medan Tuanku 2-4	3.5	level
13	Komtar 2	3.1	level	29	Medan Tuanku 2-5	3.5	level
14	Mayang Hyper Store 1-1	3.4	level	30	Wisma Sime Darby 2	3.1	level
15	Mayang Hyper Store 1-2	3.4	level	31	Wisma Sime Darby 3	3.1	level
16	Mayang Hyper Store 1-3	3.4	level				

Site No.	Lane Name	Lane Width (m)	Gradient	Site No.	Lane Name	Lane Width (m)	Gradient
Area: non-CBD							
32	Jln Gopeng-Fella1	3.1	level	48	Jln Imbi 1	3.4	-3.49
33	Jln Gopeng-Fella2	3.1	level	49	Jln Imbi 2	3.3	-3.49
34	Jln Raja Dihilir 2	3.2	level	50	Jln SS2 24-2	3.2	-5.24
35	Jln Raja Dihilir 3	3.2	level	51	Jln Tuanku Abdul Rahman 1	3.5	1.75
36	Jln SAS-Ipoh 5	3.1	level	52	Plaza Ampangan 2	3.7	-1.75
37	Jln SAS-Ipoh 8	3.2	level	53	Jln Bangsar 1	3.1	1.75
38	Jln SAS-Penang 1	2.9	level	54	Jln Bangsar 2	3.7	1.75
39	Jln SAS-Penang 2	2.9	level	55	Jln Bangsar 3	3.9	1.75
40	Jln SAS-Penang 3	2.9	level	56	Jln Dato Muda Linggi 3	3.6	1.75
41	Jln SAS-Penang 4	2.9	level	57	Jln Seremban 1	3.4	1.75
42	Juru Site 2-Lrg 1	3.2	level	58	Jln Seremban 4	4.0	3.49
43	Juru Site 2-Lrg 2-1	3.2	level	59	Jln Sungai Ujong 2	3.6	1.75
44	Juru Site 2-Lrg 2-2	3.2	level	60	Jln Utara 1	3.5	3.49
45	Pesta Pulau Pinang 1	3.4	level	61	Jln Utara 2	3.5	3.49
46	Pesta Pulau Pinang 2	3.5	level	62	Makro 3	3.6	2.62
47	Pesta Pulau Pinang 3	3.1	level	63	Makro 4	3.4	2.62
				64	Persimpangan Centre Point 1	3.0	3.49

Table 2: Results of Independent-samples t-test

	t	d.f.	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% C.I. of the Difference	
						Lower	Upper
Equal variances assumed	3.261	1420	0.001	31.59	9.69	12.59	50.60

5.2 One-way analysis of variance (ANOVA)

The results of one-way ANOVA testing are as shown in Table 3. Based on the observed significant level, which was less than 0.05, the null hypothesis was rejected and it was concluded that the means of motorcycles within flow at different lane positions were significantly different. Therefore, the lane position dummy variable had to be included in the model in order to take into account the effect of lane position on motorcycle behaviour.

Table 3 Results of One-Way ANOVA Testing

	Sum of Squares	d.f.	Mean Square	F	Sig.
Between groups	974645.6	2	487322.784	16.999	0.000
Within groups	40678721	1419	28667.174		
Total	41653366	1421			

5.3 Two-way ANOVA for motorcycles within flow

Two-way ANOVA testing on motorcycles within flow was conducted to check the effect of motorcycles within flow of two different area types (CBD and non-CBD) together with three lane positions of an approach road. Initially, the Levene's test of homogeneity of variance was carried out and the results were significant. Therefore, in order to make the variance more comparable, the data were transformed to base-10 logarithm. The results of two-way ANOVA for the transformed data are shown in Table 4. The observed significance value for the no-interaction hypothesis was 0.863 (greater than 0.05); therefore the null hypothesis of no interaction between the two factors could not be rejected. In Table 4, the F ratios were computed by dividing each of the factor's mean squares by the error mean square. If the null hypothesis for an interaction is true, then the corresponding F ratio should be close to 1.

Table 4: Result of Two-way ANOVA of Transformed Data

Source	Type III Sum of Squares	d.f.	Mean Square	F	Sig.
Model	8047.853	7	1149.693	25663.964	0.000
log M _T	44.934	1	44.934	1003.034	0.000
Area	0.410	1	0.410	9.147	0.003
Lane	2.502	2	1.251	27.927	0.000
Area*Lane	1.320E-02	2	6.601E-03	0.147	0.863
Error	63.389	1415	4.480E-02		
Total	8111.242	1422			

5.4 Modelling the behaviour of motorcycles at signalised intersections

In order to predict the number of motorcycles inside flow, M_I , from the total motorcycles observed at the sites, M_T , a regression analysis was conducted. Initially, M_I was regressed with M_T , but the variance within the data set was not constant. However, a \log_{10} transformation of both data sets yielded a good work model (see Table 5 and eqn (1)).

Table 5: Estimation of Results of Multiple Linear Regression Using Transformed Data

Variables	Coefficients		t	Sig.
	β	Std. Error		
log M_T	0.648	0.019	33.444	<0.001
D_A	0.04166	0.013	3.192	0.001
D_{P1}	0.592	0.055	10.832	<0.001
D_{P2}	0.560	0.054	10.425	<0.001
D_{P3}	0.456	0.055	8.247	<0.001

$$\log(M_i) = 0.6481 \log \log(M_T) + 0.04166 D_A + 0.592 D_{P1} + 0.560 D_{P2} + 0.456 D_{P3} \quad (1)$$

$(r^2 = 0.992)$

- where M_i = motorcycles within flow per hour
 M_T = total motorcycles observed per hour
 D_A = dummy variable for area type, where:
 D_A = 1 area type CBD)
= 0 otherwise – non-CBD areas)
 D_P = dummy variable for lane positions, where:
 D_{P1} = 1 if nearside lanes (D_{P2} and $D_{P3} = 0$)
= 0 otherwise (D_{P2} or $D_{P3} = 1$)
 D_{P2} = 1 if central lanes (D_{P1} and $D_{P3} = 0$)
= 0 otherwise (D_{P1} or $D_{P3} = 1$)
 D_{P3} = 1 if offside lanes (D_{P1} and $D_{P2} = 0$)
= 0 otherwise (D_{P1} or $D_{P2} = 1$)

A residuals analysis was conducted to test the validity of the linear regression assumptions and the results are shown in Figure 1. As the error terms were normally distributed (Figure 1A) and randomly distributed with a mean '0' (Figure 1B), the assumptions of linear regression were satisfied.

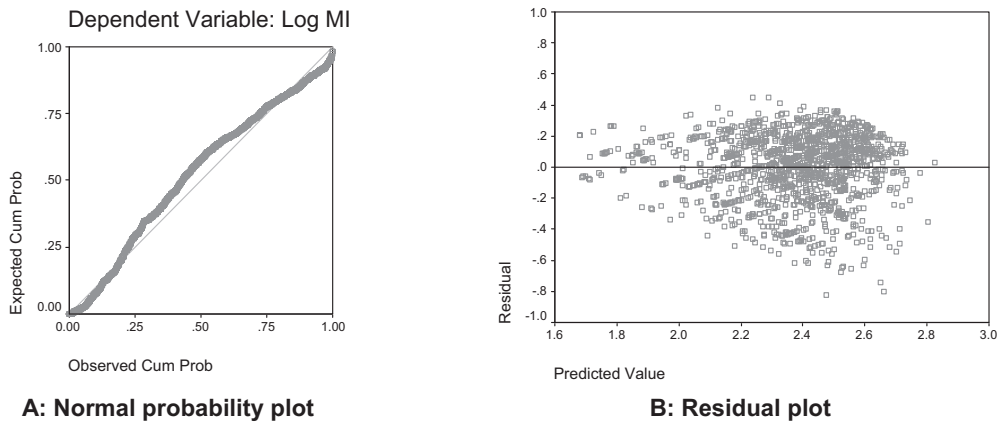


Figure 1: Results of residual analysis

6 Analysis of the Effect of Motorcycle Travel Behaviour on Saturation Flow

Saturation flow is the maximum constant departure rate from the queue during the green period. The saturation flow concept assumes that, when the signal changes to green, traffic discharges at a constant rate (saturation flow rate) until either the queue is exhausted or the green period ends. The departure rate is lower during the first few seconds as vehicles accelerate to normal running speed and similarly during the period after the end of green interval as the flow of vehicles declines (Kimber et al. 1986; Teply and Jones 1991; Akcelik 1981). The rate of discharge (saturation flow) was assumed not to vary from cycle to cycle (Miller 1968).

In a mixed traffic situation, the proportion and type of vehicles in the traffic stream also must be taken into consideration. Saturation flow usually is measured in terms of vehicles per hour (veh/h), so weighting factors, or passenger car equivalents (pce), are used for other vehicles to enable saturation flows to be stated as passenger car units per hour (pcu/h). Conventionally, the pce values used in the design and analysis of signalised intersections in Malaysia were adopted, with slight adjustment, from the values determined by Webster and Cobbe (1966) in the UK. However, due to differences in driver behaviour, traffic composition and roadway characteristics; these values may not be representative of local traffic conditions in Malaysia. These pce values have not been revised since the publication of Arahan Teknik (Jalan) 13/87 in 1987. Therefore, more realistic pce values that reflect the present Malaysian road conditions were derived using the headway ratio method described by Leong, Wan Ibrahim and Sadullah (2003). They proposed the following pce values:

e_{car}	=	1.00
$e_{\text{motorcycle}}$	=	0.44
e_{lorry}	=	1.19
e_{trailer}	=	2.27
e_{bus}	=	2.08

The pce value of 0.44 derived for motorcycles was for the within-flow only and problems will occur during traffic volume counting because motorcycles are not segregated into motorcycles within the flow and motorcycles outside the flow. Therefore, the pce value of 0.44 derived for motorcycles within flow needed to be calibrated with equation (2) to obtain a pce value for total flow of the motorcycles.

$$0.44 \times M_I = e_{\text{motorcycle calibrated}} \times M_T \quad (2)$$

where M_I is the segregation model (eqn (1)) developed in this research. The value of the calibrated pce for motorcycles therefore is:

$$e_{\text{motorcycle calibrated}} = 0.44 \times \frac{M_I}{M_T} \quad (3)$$

Hence, the effect of varying vehicles in the estimation of saturation flow rates can then be taken into consideration by using a traffic composition factor, f_c shown in equation (4).

$$S_{(\text{veh/h})} = \frac{S_{(\text{pcu/h})}}{f_c} \quad (4)$$

$$f_c = \frac{\sum q_i e_i}{q} \quad (5)$$

where q_i = flow in vehicles for vehicle type i
 q = total traffic flow
 e_i = pce of vehicle type i .

Conventionally, saturation flow rate at an intersection is estimated assuming an ideal value for saturation flow rate and then adjusting it for the prevailing conditions. For through vehicles, the equation used to estimate saturation flow rates is based on the US HCM 2000:

$$S \text{ (veh/h)} = \frac{S_o \times f_w \times f_g \times f_a}{f_c} \quad (6)$$

where S_o = ideal saturation flow rate
 f_a = area type adjustment factor
 f_w = lane width adjustment factor
 f_g = gradient adjustment factor
 f_c = traffic composition factor

Based on eqn (5), the traffic composition factor, f_c , can then be determined using equation (7).

$$f_c = f_{car} + f_{hv} + f_m \quad (7)$$

where

$$f_{car} = e_{car} \left(\frac{q_{car}}{Q} \right) \quad (8)$$

$$f_{hv} = e_{trailer} \left(\frac{q_{trailer}}{Q} \right) + e_{lorry} \left(\frac{q_{lorry}}{Q} \right) + e_{bus} \left(\frac{q_{bus}}{Q} \right) \quad (9)$$

$$f_m = e_{motorcycle \text{ calibrated}} \left(\frac{M_T}{Q} \right) \quad (10)$$

$$Q = q_{car} + q_{trailer} + q_{motorcycle} \quad (11)$$

The methodologies used to estimate saturation flow in Malaysia were revised by the Ministry of Works Malaysia and more realistic ideal saturation flow rate and adjustment factors that reflect the present Malaysian road conditions were presented in the Malaysia Highway Capacity Manual 2006 (Ministry of Works Malaysia 2006). A value of 1,930 pcu/hr was used for the ideal saturation flow rate. In terms of adjustment factors, the following equations were used.

f_a : area type adjustment factor = 0.8454

f_w : lane width adjustment factor = $1 + \frac{w - 3.66}{3.663}$

f_g : gradient adjustment factor

downhill gradient adjustment factor: $f_{g(\text{downhill})} = 1 - \frac{\%G}{26.34}$

uphill gradient adjustment factor: $f_{g(\text{uphill})} = 1 - \frac{\%G}{14.39}$

Based on the US HCM 2000, only two categories of vehicles were considered: passenger cars and heavy vehicles. The equation used to calculate saturation flow rate was:

$$S \text{ (veh/h)} = S_o \times f_{HV} \times F_w \times f_g \times f_a \quad (12)$$

where $f_{HV} = \frac{100}{100 + \%HV(E_T - 1)}$; $E_T = 2.0$ pcu/HV

ideal saturation flow rate (S_o) = 1,900 pcu/h

area type adjustment factor (f_a) = 0.90

lane width adjustment factor (f_w) = $1 + \frac{w - 3.66}{9}$

$$\text{gradient adjustment factor } (f_g) = 1 - \frac{\%G}{200}$$

In Arahan Teknik (Jalan) 13/87, the base saturation flow is predetermined based on lane width (Table 6) and no adjustment factor for type of area was therefore required.

Table 6: Relationship Between Effective Lane Width and Basic Saturation Flow

W (m)	3.0	3.25	3.5	3.75	4.0	4.25	4.5	4.75	5.0	5.25
s (pcu/hr)	1845	1860	1885	1915	1965	2075	2210	2375	2560	2760

For every 1% increment in uphill gradient, the saturation flow was reduced by about 3% and vice versa for a downhill gradient. The equation used to compute saturation flow is:

$$S(\text{veh/h}) = \frac{S_{\text{base}} \times f_g}{f_c} \quad (13)$$

The pce values used in Arahan Teknik (Jalan) 13/87 were:

$$\begin{aligned} e_{\text{car}} &= 1.00 \\ e_{\text{motorcycle}} &= 0.33 \\ e_{\text{lorry}} &= 1.75 \\ e_{\text{trailer}} &= 2.25 \\ e_{\text{bus}} &= 2.25 \end{aligned}$$

A comparison between the saturation flow rates estimated in this study with values estimated using the US HCM 2000 (Figure 2) shows that US HCM 2000 consistently under-estimates the saturation flow rates in Malaysia and that this standard is not applicable in Malaysia. But on the other hand, comparison between the saturation flow rates estimated in this study with values estimated from Arahan Teknik (Jalan) 13/87 (Figure 2) showed that Arahan Teknik (Jalan) 13/87 generally over-estimated saturation flow rates, which would lead to an over-estimation of capacity and hence over-designed signalised intersections, an uneconomic and inefficient use of the signalised intersection.

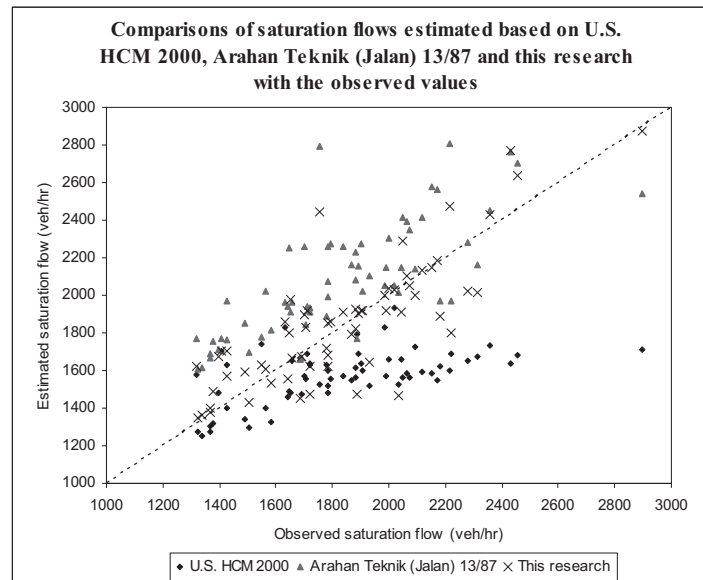


Figure 2: Comparison of estimated saturation flow values with observed values

The developed model predicted saturation flow values similar to the observed values (predicted saturation flow = 1.005 x observed saturation flow; $R^2 = 0.998$) with only 0.5% over-prediction. These results suggest that the saturation flow model developed in this research predicts motorcycle travel

behaviour well. When the behaviour of motorcycles is considered in estimating the saturation flow, signalised intersections are more efficient in terms of performance and traffic accidents are reduced.

7 Conclusions

Motorcycles travelling through a signalised intersection can be divided into different categories. Different motorcycle travel patterns have different impacts on traffic flow. Motorcycles that travel through the intersection following the queuing discipline of first-in-first-out have significant effects on saturation flow rates.

A model that describes motorcycle travel behaviour at signalised intersections was derived. By adjusting the flow of motorcycles, a pce value for motorcycles could be determined, and saturation flow rates at signalised intersections predicted more accurately. Comparisons between saturation flow rates estimated using the US HCM 2000 and values observed in the field showed that the US HCM 2000 consistently under estimated the saturation flow rates observed at signalised intersections in Malaysia. It can therefore be concluded that the high percentage of motorcycles in Malaysia significantly affects the capacity of signalized intersections.

Comparisons between saturation flow rates estimated based on Arahan Teknik (Jalan) 13/87 (which does not take motorcycle travel behaviour into consideration) and values observed in the field showed that this standard over-estimated the saturation flow rates. Over-estimation of saturation flow rates may affect traffic flow because wider lanes are needed to satisfy the higher traffic flow. However, with wider lane widths, motorcycles will become a nuisance and sometimes a danger to other road users due to their ability to weave in and out of other moving vehicles. Clearly, the integration of motorcycle travel behaviour in to the estimation of saturation flow rates is crucial for designing safer and more efficient signalised intersections in Malaysia.

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Environment and Road Safety in Malaysia*

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ABSTRACT

There are approximately 6,000 fatalities in Malaysia annually, or 3.7 deaths per 10,000 registered vehicles. The Government of Malaysia has set a target of 2 deaths per 10,000 registered vehicles by 2010. Malaysia uses the integrated planning matrix where the emphasis in safety initiatives is focused on human, vehicle and environment factors, at both the pre-crash, crash and post-crash stages. The road environment initiatives are described in this paper. The Highway Development and Management model (HDM-4) has been used to manage the road asset in Malaysia for more than 10 years. Other road safety initiatives are also in place to improve safety throughout Malaysia though funding is limited. All initiatives are either preventive or reactive. These initiatives are briefly described in this paper.

1 Introduction

Malaysia consists of 13 states and three Federal territories. As it is located near the equator, the climate is characterized as tropical. It has a population of 26 million, including 50% Malays, 30% Chinese, 12% Indians and 8% others. It has an area of 329,847 km². The capital city is Kuala Lumpur, but the seat of the Federal Government is located in Putrajaya.

There are approximately 6,000 fatalities in Malaysia annually, or 3.7 deaths per 10,000 registered vehicles. The Government of Malaysia has set a target of 2 deaths per 10,000 registered vehicles by 2010.

An integrated planning matrix is used in Malaysia, where the emphasis on safety initiatives is focused on human, vehicle and environmental factors, at both the pre-crash, crash and post-crash stages. The road environment initiatives are described in this paper.

The Highway Development and Management model (HDM-4) has been used to manage the road asset in Malaysia for more than 10 years. Other road safety initiatives are also in place to improve safety throughout Malaysia though funding is limited. All initiatives are either preventive or reactive. These initiatives include:

- road safety audit
- blackspot treatment
- motorcycle lanes program – exclusive and non-exclusive
- traffic management during construction
- iRAP
- improve clear zones and barrier systems.

These initiatives are now briefly described.

* This paper is based on a presentation to the 8th Heads of Road Authorities (HORA) meeting in Tokyo in 2008.

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2 Road-Related Road Safety Initiatives

2.1 Road Safety Audit

Road safety audits of new projects has been conducted in Malaysia since 1994. It is compulsory for all new Public Works Department (PWD) projects. Audits are carried out at five different stages of project implementation: feasibility, preliminary design, detail design, construction and pre-opening, and operation. Road safety audits are also carried out on existing roads.

2.2 Blackspot Investigation and Treatment

The accident blackspot investigation includes identifying and prioritizing sites, ranking blackspots sites, accident analysis, diagnosis and the selection of possible countermeasures.

Different weightings are assigned to different types of accident as follows: fatal (6 points), severe injury (4 points), slight injury (2 points) and damage-only (1 point). The prioritization is carried out using the total weighting points from highest to lowest, with the highest coinciding with the worst location.

2.3 Motorcycle Lane Programs

Segregation of motorcycles from the mainstream traffic is one of the road safety initiatives. The locations of accidents involving motorcycles were identified and included in the motorcycle lane program. There are two types of motorcycle lanes: exclusive and non-exclusive motorcycles. The exclusive lanes fully segregate motorcycles from the other traffic (Figure 1), whereas the non-exclusive motorcycle lane involves the use of the paved shoulder with chevron marking used to separate the traffic from the motorcycles (Figure 2). Since the implementation of the exclusive lanes, there has been a reduction of approximately 30%.



Figure 1: Exclusive motorcycle lane
(Source: MIROS Library)



Figure 2: Non-exclusive motorcycle lane
(Source: MIROS Library)

2.4 Traffic Management During Construction

Since 2004, the PWD has assigned a provisional sum of money for new projects to traffic management and diversion costs. This has resulted in more appropriate traffic management planning and execution. The contractors are given, and are expected to have, more accountability should an accident take place at a construction site.

2.5 iRAP

On 14th March 2007, the International Road Assessment Program (iRAP) was officially launched to kick-start a 3-month pilot study in Malaysia. MIROS was part of the steering group and project team headed by the Road Safety Department (JKJR) and the Automobile Association of Malaysia (AAM). iRAP is a non-profit company registered in England with funding support from the FIA Foundation for the Automobile and Safety. Its primary goal is to reduce the road toll in low and middle income countries. Malaysia was selected as the preferred country for the iRAP pilot study in the Asian Region.

A total of 3687 km of expressways and Federal roads were surveyed over a five-week period. The roads were rated in terms of safety. The key outcomes of the study were as follows:

- a 5 star map of the pilot study network
- cost-efficient and effective countermeasure programs
- an estimate of the economic benefits of road safety investment
- a web-based tool for analyzing potential countermeasure programs
- increased local road safety capability, capacity and international support and contacts.

An example of a star map for car drivers is shown in Figure 3. Star mapping was also carried out for motorcyclists, pedestrians and cyclists.

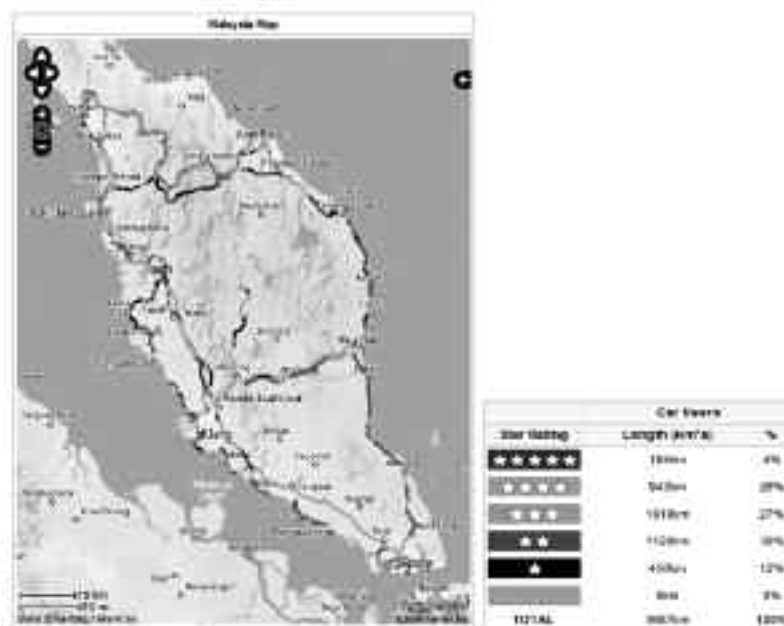


Figure 3: Star map for car drivers

2.6 Clear Zones and Barrier Systems

Having a proper understanding of the clear zone concept is one of the major issues faced by road authorities. With limited right-of-way and the type of linear development found in Malaysia it is quite difficult to provide adequate clear zones. One of the countermeasures suggested in the iRAP study was to eliminate all roadside hazards, thus increasing the clear zone area.

The standards for barriers used on Malaysian highways and federal trunk roads are also being reviewed. It was clear from the crash investigation that there were many cases where the barrier system failed. The upgrading of the current barrier standards is therefore urgently required.

3 Crash Investigation Case Studies

The major probable causes of road accidents identified from the investigation conducted by MIROS were:

- collisions with trees
- hydroplaning on road surfaces
- safety/health environment associated with bus public transportation
- rear seat belts
- speeding
- barrier failure
- crash compatibility
- fatigue.

The impact of a vehicle hitting a tree located within the road corridor is shown in Figure 4 and Figure 5.



Figure 4: Tree within the road corridor
(Source: MIROS Library)



Figure 5: Vehicle after hitting the tree in Figure 4
(Source: MIROS Library)

Road Fund: A Tool For Asset Preservation In Bangladesh

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ABSTRACT

The Roads and Highways Department (RHD) of Bangladesh is the main road authority in Bangladesh. It has a sound pavement management system (PMS), which consists of data collection, a road database and use of the Highway Development and Management (HDM-4) model for asset preservation. However, RHD's backlog is increasing regularly due to its assets not being maintained on time owing to a lack of sufficient funding. In this paper, relevant Government policies in the transport sector and the new Road Master Plan, directed especially on maintenance, are reviewed. It is concluded that increased road funding would be the long-term solution for road network management in Bangladesh.

1 Introduction

The prime responsibility of the Roads and Highways Department (RHD), Bangladesh, is to construct and maintain major roads, bridges and ferries in the main road network. RHD's vision is to provide safe, cost-effective and well-maintained roads. RHD is responsible for about 20,800 km of roads and about 15,000 bridges and culverts (RHD 2007). In 2000, the replacement value of RHD's road-related assets was estimated to be approximately US\$7,400 million (Ministry of Communications 2000). Recent estimates show that RHD has about US\$3,650 million of paved road assets and a backlog of US\$600 million (RHD 2007). RHD requires, on average, US\$ 200 million for maintenance and backlog removal over the next five years (RHD 2007).

This data reveals that efficient and timely maintenance is necessary to preserve these huge road assets and to remove the backlog. Both the National Land Transport Policy (NLTP 2004) and the Road Master Plan (RHD 2007) emphasised the need for timely maintenance and the removal of the backlog. As timely maintenance can optimise transport costs, an effective Pavement Management System (PMS) is essential for the efficient maintenance management in RHD.

RHD's PMS is shown in Figure 1. Details of the components are described elsewhere (Khan 2005 and 2007). The RHD uses the Road Maintenance and Management System (RMMS) database as input to the Highway Development and Management (HDM-4) model to preserve its assets. The HDM-4 model is the key tool in preserving its huge assets by providing cost-effective solutions on network maintenance. It uses the RMMS database as input.

The use of the HDM model commenced in 1995 with the Highway Design and Maintenance Standards Model (HDM-III) and then HDM-4: Version 1.3 (Khan 2004). It is used to provide whole of life-cycle analysis of road pavement performance in response to user-specified investment alternatives. Appropriate quality data (road condition, traffic, roughness, etc.) and calibration of the key performance relationships are essential to provide credible HDM-4 results, and this has been done for Bangladesh (Khan 2005). The HDM-4 prioritised outputs are being used for budget estimation, programming, treatment selection, design, tendering and implementation.

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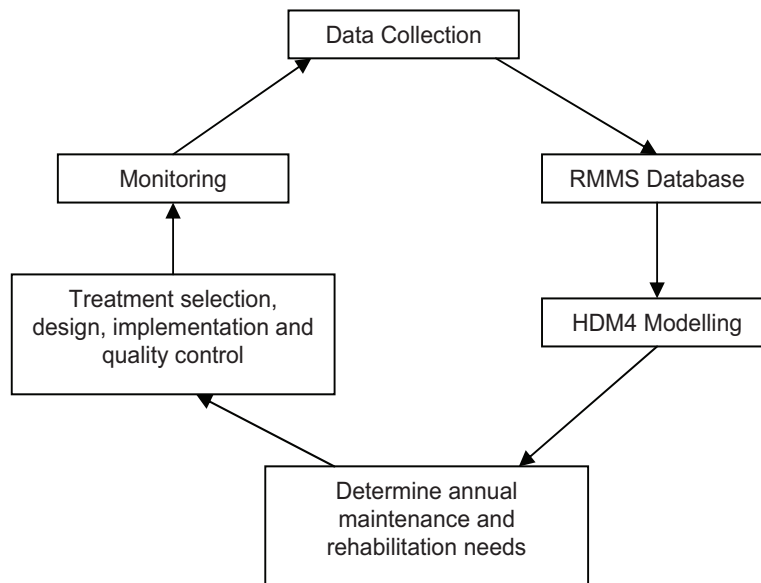


Figure 1: Role of HDM-4 model in the RHD-PMS (RHD 2007; Khan 2007)

Whilst road maintenance has been given major emphasis in different Government policies, this is not the case in reality, as the functional and structural road conditions in Bangladesh are deteriorating. Therefore, a review of Government policies and planning is necessary if a road maintenance plan is to be implemented that more efficiently preserves the road asset.

The following approaches to obtaining a more favourable implementation of Government policies with respect to road maintenance are considered in this paper:

- review of the Government policies with respect to maintenance planning
- establish a correlation between these policies and road maintenance planning
- make recommendations for more effective road asset preservation.

2 Millennium Development Goal and Poverty Reduction Strategy

At the United Nations Millennium Summit in 2000, the UN declared the Millennium Development Goal (MDG). It had the following eight components:

- eradicate extreme poverty and hunger
- achieve universal primary education
- promote gender equality and empower women
- reduce child mortality
- improve maternal health
- combat HIV and AIDS, malaria and other diseases
- ensure environmental sustainability
- develop a global partnership for development.

It was considered that each country should develop its own policy to achieve the MDG. In order to achieve the MDG, Bangladesh set its Poverty Reduction Strategy (PRSP) to achieve a Gross Domestic Product (GDP) at 6-7% (PRSP 2005). The major characteristics of the PRSP are:

- accelerated poverty reduction (macroeconomic environment promoting growth, pro-poor economic growth, safety nets for the poor and human development)
- social access

- improvement in health and education
- ensure gender equality
- rural industrialisation
- good governance.

It was considered that both the MDG and PRSP emphasis on poverty reduction, economic development, GDP, social development, education, health and nutrition facilities was correct. Several studies ensured that road infrastructure development could help achieving these goals (Sikder 2002; Ahmed and Hossain 1990; Lin and Song 2002 and Nagaraj et al. 2000).

Better, well-maintained roads can help achieve greater agriculture output, higher income, improved health services and greater wage income opportunities. The Government's 5th five-year plan (1997-2002) also emphasised the role that efficient transport systems can play in economic development and poverty reduction. Efficient road works which improve the quality of the road lead to short-term benefits in terms of jobs, economic development, social development and improvement in the GDP; long-term benefits include economic stability and a positive change in the culture of the society (Sikder 2002).

Ahmed and Hossain (1990) found that road development had a strong positive influence on incomes of the poor. Villages with better road access were generally better off, because of the resulting agricultural benefit. It was found that infrastructure development increased household income by 33%, doubled wages, and increased income from business and industries by 17%. Ahmed and Hossain also concluded that better infrastructure related to greater agricultural outputs, higher income, better indicators of access to health services and greater wage income opportunities.

Nagaraj et al. (2000) found that, in India, a 10% increase in the road network could result in a 3.4% increase in per capita income. They found that power consumption and health conditions positively correlated with the availability of road infrastructure. Lin and Song (2002) observed that the provision of paved roads was positively related to a growth in the GDP per capita in urban areas.

This discussion demonstrates that all the policies and planning rightly with respect to road works deal with poverty reduction, economic development, GDP, social development, health, education and nutrition facilities. A recent World Bank Study (IMF 2006) showed that road maintenance had a positive effect on GDP in several countries (see Figure 2).

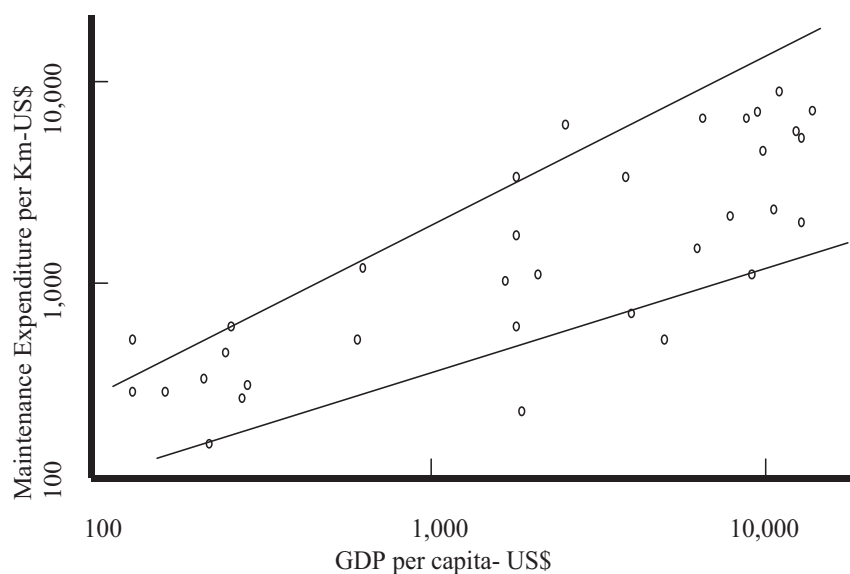


Figure 2: Relationship between road maintenance expenditure and GDP (IMF 2006)

3 Government Policies in the Transport Sector

The Government of Bangladesh recently developed the National Land Transport Policy (NLTP), THE Integrated Multimodal Transport Policy (IMTP) and the Road Master Plan to implement and ensure efficient road projects so that the PRSP can be attained. These are now briefly discussed.

3.1 National Land Transport Policy (NLTP)

The NLTP was formulated in the light of the Government pledge to establish a transport system which was safe, cheap, modern, technologically dependable, environment friendly and acceptable in the light of globalisation. It had a long term vision of at least 30 years to make the role of transport in economic activities more significant and to strengthen continued economic and social development. The NLTP reflected a multi-modal transport system so that transport opportunities were optimised (NLTP 2004).

3.2 Integrated Multi-Modal Transport Policy (IMTP)

The IMPT was developed to combine road transport with railways, civil aviation and inland water transport. Its vision is to provide safe, dependable, effective, efficient and fully integrated transport operations and infrastructure which will best meet the needs of freight and passengers by improving levels of service and minimising costs in an effective manner. It supports Government strategies for economic and social development whilst being environmentally and economically sustainable. In addition, it will make the transport system more efficient in a regional context and allow Bangladesh to exploit its unique geographical position (IMTP 2006).

3.3 RHD Road Master Plan

In 2007, the RHD developed its Road Master Plan (RMP) for the next 20 years under a project funded by the Asian Development Bank. It highlights the importance of maintenance for sustainability. This plan also emphasises vehicle overloading, drainage and routine maintenance. Some key features of the plan are discussed later in this paper.

3.4 Government Policies on Road Maintenance

- The Government policies on road maintenance are shown in Table 1, whilst the relationship between the MDG, PRSP, NLTP, IMTP and the Road Master Plan is shown in Figure 3.

Table 1: Characteristics of Government Policies on Maintenance

Govt. Policies	Key Transport Issues	Key Road Maintenance Issues	Comment
PRSP (2005)	<ul style="list-style-type: none"> Strategic national highway for economic development Rationalisation of sectoral initiative Setting appropriate pricing policy Reduction of system loss Sectoral restructuring Good governance 	<ul style="list-style-type: none"> Maintenance and improvement of road network to raise quality Allocation of fund from development head to maintenance Road fund 	<ul style="list-style-type: none"> Economic growth and poverty reduction can be achieved by road maintenance
NLTP (2004)	<ul style="list-style-type: none"> Improvement of transport sector Road network development Strategic road Private sector participation Urban traffic management Community transport systems Parking policies Automatic traffic control Safety Good governance Proper utilisation of transport resources 	<ul style="list-style-type: none"> Frequent routine and periodic maintenance to provide value for money Removal of backlog Performance Based Maintenance (PBM) Public Private Partnership (PPP) Road fund Sufficient funding and expenditure Asset management Toll roads 	<ul style="list-style-type: none"> Improvement of transport sector and lower income groups Road maintenance is properly addressed

Table 2 (con't)

Govt. Policies	Key Transport Issues	Key Road Maintenance Issues	Comment
IMTP (2006)	<ul style="list-style-type: none"> Multimodal transport system 		<ul style="list-style-type: none"> Economic development and poverty reduction would be achieved
RHD Road Master Plan (2007)	<ul style="list-style-type: none"> Best use of assets for road users Strategic road corridors for economic development Linkage of rural roads Protection of environment Enhancement of accountability and transparency 	<ul style="list-style-type: none"> Maintain roads in good condition Long term maintenance budget Major roads rehabilitation and recovery 	<ul style="list-style-type: none"> Road maintenance Corridor roads Economic development Poverty reduction Rural roads Social access Proper economic growth

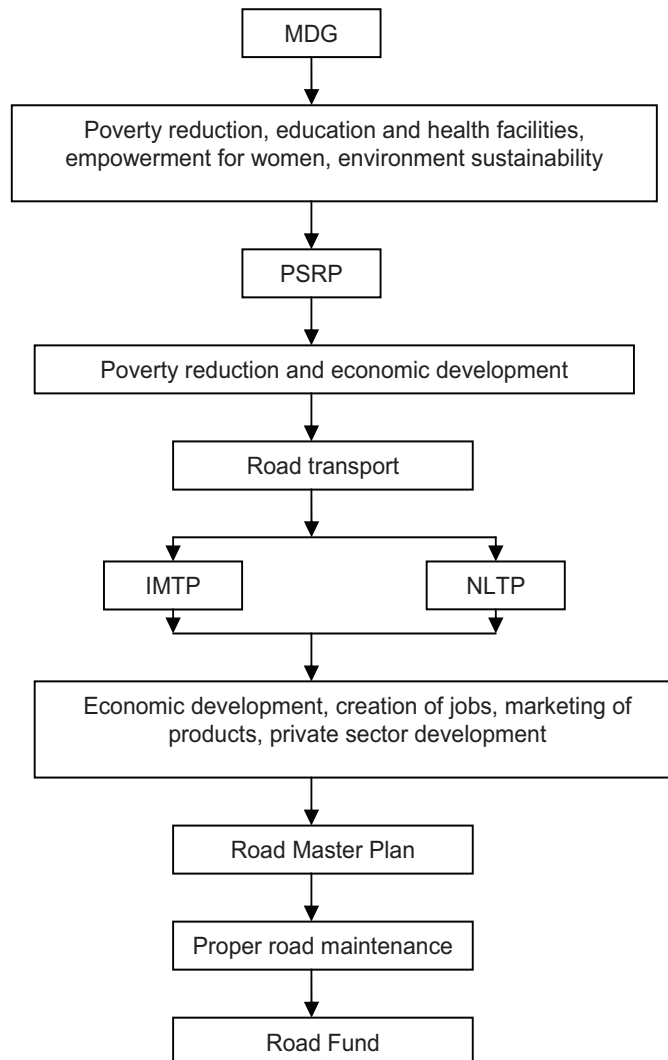


Figure 3: Relationship between Government policies on road maintenance

It can be seen from Table 1 that the following issues are vital for road asset preservation and economic development:

- sufficient funding
- backlog removal

- regular routine and periodic maintenance
- PBM and PPP
- asset management through road funding.

4 Current Situation in RHD

4.1 Recent Results

It was mentioned earlier that the maintenance of roads was not being properly addressed in Bangladesh. This is confirmed by the data in Table 3, which reveals that sufficient funding was not being provided to preserve the road asset. As a result, the road network is not performing well (see Figure 4).

Table 3: Maintenance Demand and Expenditure in Bangladesh (RHD 2007)

	HDM Demand on Periodic Maintenance (million taka*)	Expenditure on Periodic Maintenance (million taka)	Expenditure on Periodic Maintenance (%)	Comments
2001-2002	8,270	790	9.56%	Sufficient funding was not provided to preserve road assets
2002-2003	7,560	1,000	13.23%	
2003-2004		2,000		
2004-2005	5,265	3,392	64.43%	
2005-2006	6,527	3,450	52.86%	
2006-2007	17,141	3,667 (to April 2007)	21.40%	

* 100 Bangladesh taka = US\$1.45 (January 2010).

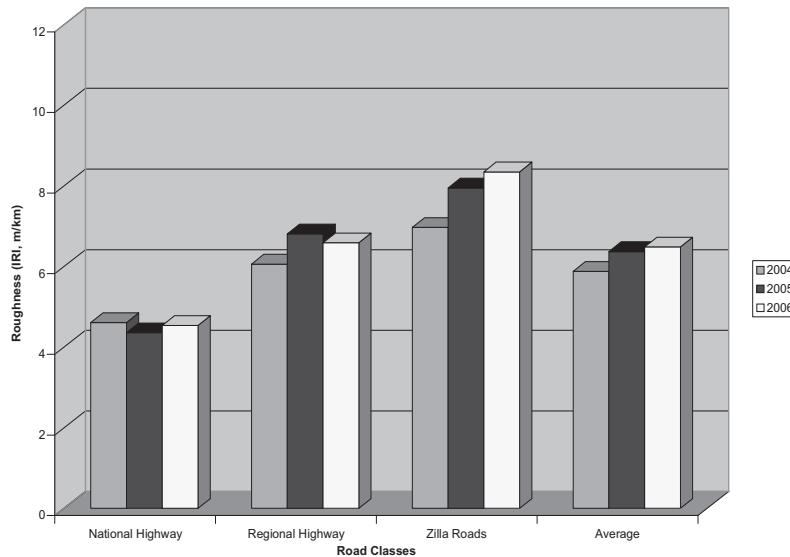


Figure 4: Average network roughness according to road class (2004-2006) (RHD 2007)

Recent analysis using the HDM-4 model suggested that the routine and periodic maintenance required 30% of the budget and 70% for rehabilitation and reconstruction during the first year to preserve the road asset. The total maintenance demand was estimated to be US\$1,000 million and that, on average, US\$200 million was needed over the next five years (see Figure 5) (RHD 2007). It was also found that, if the network was maintained initially with appropriate treatments, in the long term the condition of the roads would be good to fair with only routine and periodic maintenance necessary. The analysis revealed that, assuming a hypothetical deferred maintenance of US\$45 million per year, because insufficient funding was available, the average five years requirement would be US\$250 million (RHD 2007).

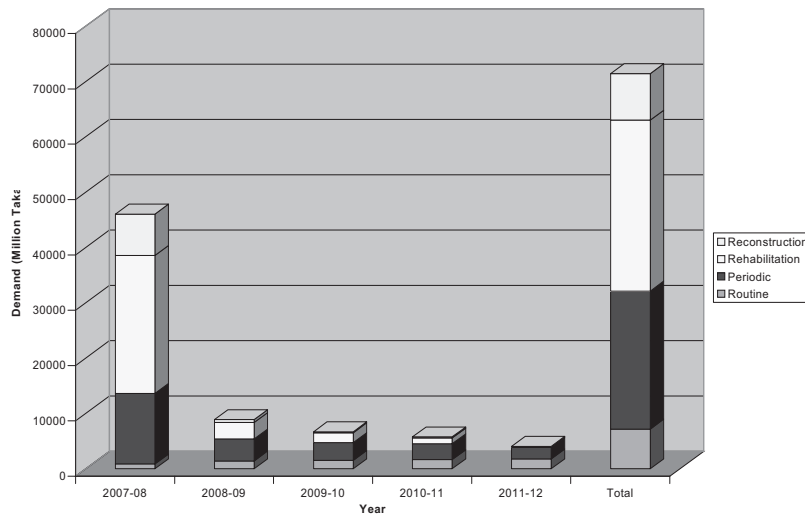


Figure 5: Treatment demand for the road network (RHD 2007)

5 Road Funding

The PRSP stated that the Government will “explore various options for financing road maintenance and operation and consider establishing an autonomous road maintenance fund to ensure adequate stable financing of roads” (RHD 2006). Its main objective is to gradually replace the Government's contributions from the general budget, with maintenance costs to be financed by the progressive implementation of a road user charge system to ensure sustained funding. It is believed that, by 2012, road users will pay the full costs of road maintenance in Bangladesh. The draft Road Fund Act (RHD 2006) specifies a set of road user charges and other sources of revenue. Major sources of road funding are:

- a surcharge on the price of petrol, octane, diesel and CNG fuel (fuel levy)
- international transit charges to be paid by foreign vehicles operators
- charges imposed on vehicles according to their size and weight
- vehicle license fees
- road and bridges tolls
- route permits charges.

6 Conclusions

The Roads and Highways Department (RHD) of Bangladesh is the main road authority in Bangladesh. It has a sound pavement management system (PMS), which consists of data collection, a road database and use of the Highway Development and Management (HDM-4) model for asset preservation. However, RHD's backlog is increasing regularly due to its assets not being maintained on time owing to a lack of sufficient funding. In this paper, relevant Government policies in the transport sector and the new Road Master Plan, directed especially to maintenance, are reviewed. Recent studies conducted by the RHD have shown that the current level of maintenance funding is not sufficient to preserve the road network. The total maintenance demand was found to be about US\$1000 million and, on average US\$200 million is needed over the next five years to remove backlog and for proper maintenance. A mechanism therefore needs to be established to ensure that sufficient funding is available for road maintenance. The proposed road fund described in this paper would be the main solution for road asset preservation in the future.

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The Development of an Accident Black Spot Program in Singapore

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ABSTRACT

A black spot program (BSP) is a road safety engineering strategy that uses pre-defined criteria and targets to identify and treat accident-prone locations. Singapore's BSP was commissioned in 2005, after years of preparatory work. Most developed countries have defined their own black spot criteria and developed their own strategies based on their individual traffic and accident histories. This is a vital step if a cost-effective reduction in highway accidents is to be achieved. The purpose of this paper is to discuss the Singapore BSP and to present some initial findings.

1 Introduction

A black spot program (BSP) is a road safety engineering strategy that uses pre-defined criteria and targets to identify and treat accident-prone locations. Singapore's BSP was commissioned in 2005, after years of preparatory work. There are two important factors that are required in carrying out a BSP: the setting up of a reliable accident database, and the development of an accident analysis software, in this case the Traffic Accident Analysis Module (TAAM).

BSPs are an important reactive approach to accident reduction. Most developed countries have defined their own black spot criteria and developed their own strategies based on their individual traffic and accident histories. This is a vital step if a cost-effective reduction in highway accidents is to be achieved. The systematic use of this concept has led to significant improvements in the field of road safety. It has also permitted the identification of the most evident safety problems linked to road design. Australia commenced their BSP in 1990 and their evaluation studies have concluded that that "BSP was a good investment for the Australian community" (Bureau of Transport Economics 2001).

Although human factors are involved in the majority of accidents, it is often more effective to apply road safety engineering treatments to the road environment, so that the interaction between the human and the environment can be modified. It is usually more difficult to change behaviour than to change elements of the road environment that induce inappropriate behaviour. The initiation of BSP in Singapore is thus an important step in introducing world-best practice to improve road safety for the benefit of the society.

The purpose of this paper is to discuss the Singapore BSP, which capitalised on the international good practice, and to present some initial findings.

2 Definition of a Black Spot Site

The most common way of defining a black spot site is by analysing accident statistics. There are three key elements in defining a black spot site: the number of accidents, the length of road section and the time of the accident. A black spot site is a site, or specific length of route, where a high number of crashes resulting in deaths or injuries occur.

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The definition of black spots and routes varies across different countries. It is influenced by trends, expectations, accident histories and the resources available to manage the BSP. Singapore uses the criterion of more than 15 accidents per site, or route, over three years, taking into consideration the severity of the accidents (i.e. fatal, serious or slight injury).

3 Methodology

There are four elements to a black spot programme: (i) identify the sites, (ii) diagnose the problems, (iii) select and implement treatments, and (iv) monitor and evaluate the treatment.

3.1 Identification of Black Spot Sites

The accident analysis software – Traffic Accident Analysis Module (TAAM) – is used in Singapore to assist in the identification of potential black spot sites. Three years of accident data are usually used to reflect the latest accident situation.

The system is able to generate black spots on intersections, expressways and arterial/collector roads. The definition of a black spot differs for each type of location. The black spot layers can be saved and retrieved later so that users can identify trends and the geographical distribution of the black spot sites. An example of generated black spot sites at intersections is shown in Figure 1. All accidents within a boundary of 100 metres from the intersection can be clustered and considered as black spots. The size can be adjusted accordingly user needs. The total number of accidents in each site is summed and ranked to identify the intersections to be studied based on the threshold (or range) set by the user.

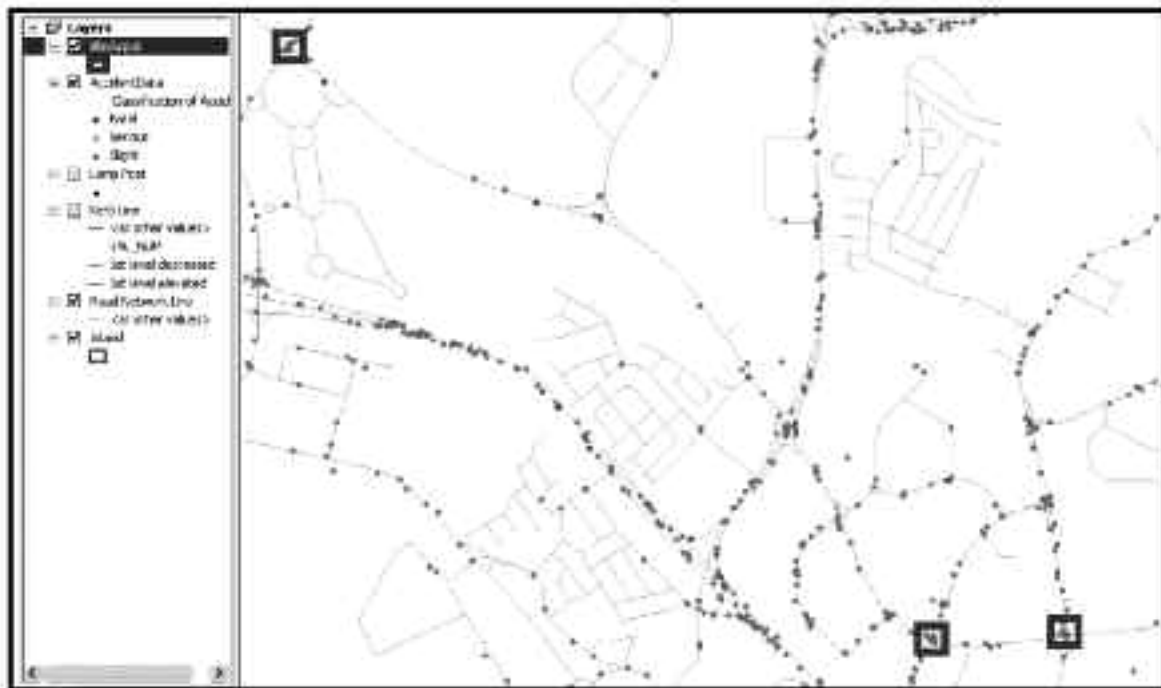


Figure 1: An example of a black spot analysis

TAAM then generates a prioritised listing of locations of varying severity based on selected parameters. Based on this list, road safety engineers gain an overview of the severity of the accidents at each identified location and prioritise the treatment to be carried out. As such, they can focus on problematic sites and target the treatment in a cost effective manner.

3.2 Diagnosis of the Problem

After identifying the sites to be studied, data analysis and site investigations are carried out to identify the likely factors contributing to the accidents. Data analysis includes examining accident patterns in terms of accident type, contributory factors and locations, accident numbers and road users (e.g. vulnerable road

users), etc. This is achieved using statistical analysis and an examination of collision diagrams. An example of a collision diagram which gives a schematic representation of vehicle and other road users' movements occurring at a given location is shown in Figure 2. It highlights the predominant accident types and the vehicle manoeuvres. Since accidents are random events, they are generated based on five years of data so that there is sufficient data to give a clearer indication of the problem(s).

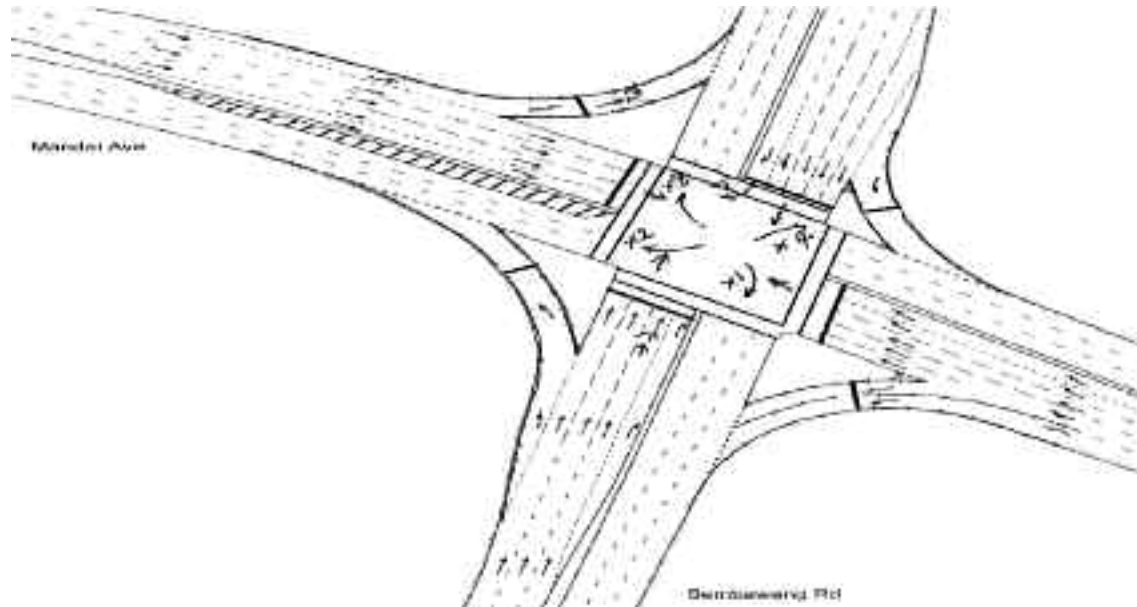


Figure 2: Collision diagram

After identifying the potential contributing factors, site investigations are then carried out and the potential problem(s) that resulted in the predominant accident types determined. On-site observations of layouts, signing, markings and traffic movements can often reveal possible reasons as to why accidents are occurring that may not be obvious from a study of maps and accident reports alone.

3.3 Selection and Implementation of Treatment

After the investigative work is completed, potential treatment options are explored for each black spot location. Once the most suitable treatment is identified, liaison between the relevant Government Departments, as well as external agencies such as the Traffic Police, is required. For example, if it is decided to carry out resurfacing work to improve the skid resistance on a stretch of expressways, then liaison with the Road Maintenance Department is required. Similarly, if the investigation showed that the black spot sites had a high proportion of accidents related to running a red light, then the Traffic Police need to be informed so that they can consider the installation of red-light cameras at the site.

3.4 Monitoring and Evaluation of Treatment

After the treatment has been implemented, the sites need to be monitored closely, both of the accident data as well as at the particular site. This is important to ensure that the treatment did not introduce undesirable side effects such as congestion or contribute to a rise in other accident types. In cases where the number of accidents does not reduce after a year, the site should be re-evaluated and additional treatments recommended. In order to obtain statistically significant results, the before-and-after study shall only be conducted three years after the treatment was installed.

4 Case studies

The following are two examples of black spot sites that have been investigated and treated.

4.1 Bedok North Rd/Bedok North Ave 1

This is a three-lane by three-lane intersection located in a residential area. A detailed study of the data revealed that the 'right-turn-against-through' accident was the predominant accident type. Motorists are

allowed to make a right turn using gaps in the traffic during the green phase when through traffic from opposite approach is also allowed to travel through the intersection (Figure 3). As such, accidents often occurred due to the driver misjudging the length of the gap and the time they had to make their turn.

The solution was to install traffic lights with red-amber-green (RAG) arrows to fully control the right-turning movement (Figure 4). Motorists must wait for the green arrow before they are allowed to make a right-hand turn. In the two years before the treatment, there were 15 accidents; in the two years after the treatment, the number of accidents had reduced 3 (i.e. an 80% reduction in the number of accidents).



Figure 3: Before treatment: vehicles waiting at the right-turning pockets for a gap to make a right turn

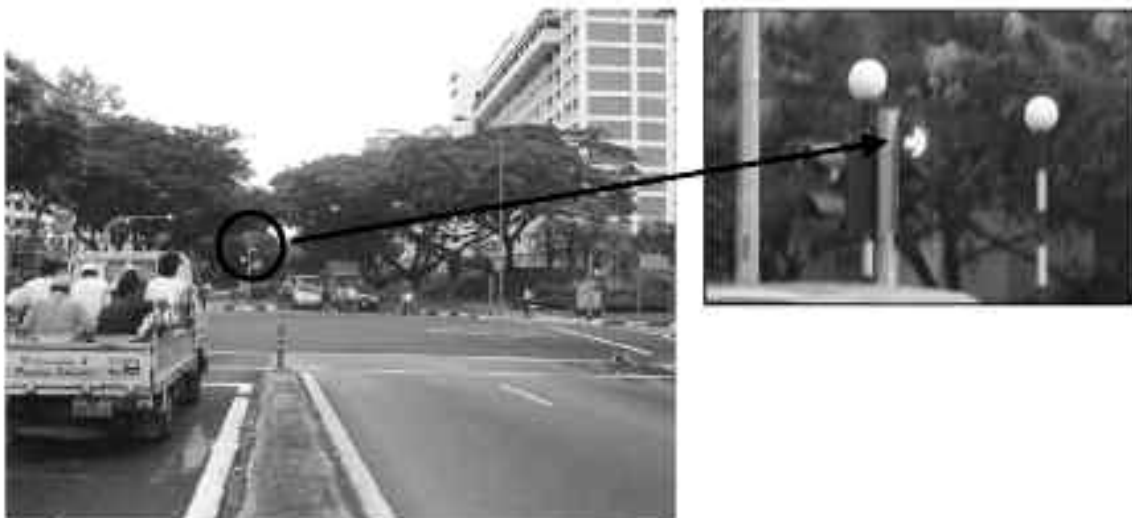


Figure 4: After treatment: right-turning vehicles wait behind the Stop line for the green arrow

4.2 SLE/BKE Expressway Interchange

This is a single-lane road that leads from SLE into BKE towards Woodlands. The predominant accident type was motorcycle accidents due to loss of control through skidding. As a result, the road was resurfaced to improve skid resistance, the lane width was narrowed and the speed regulating strips zones were lengthened to reduce speeding. During the 17 months before the treatment, there were 21 accidents; 17 months after the treatment, the number of accidents had reduced to 3 (i.e. an 86% reduction).

5 Progress in BSP Implementation

The implementation of the BSP in Singapore is currently in the third phase. To date, 97 black spot sites at junctions, expressways, expressway-interchanges and ramps have been identified, investigated and treated. Singapore, being a highly urbanised city, has a dense road network with a high proportion of junctions. Crossing and turning manoeuvres at junctions create vehicle-vehicle, vehicle-pedestrian and vehicle-bicycle conflicts and, as such, are likely locations for concentrations of accidents. The strategy is therefore to target junctions initially and then other types of roads such as expressways with tight geometry or low skid resistance, ramps and arterial roads.



Figure 5: Before treatment



Figure 6: After treatment

Preliminary before-and-after studies show positive results for most of the junctions. However, as the post-treatment duration has not reached the threshold of three years for the results to be statistically significant, no firm conclusions can be drawn at this stage. Based on current criteria, the number of accident sites to be studied should reduce. The criteria could then be adjusted to other sites needing treatment. Vulnerable road users such as pedestrians and motorcyclists are also target groups for BSP. However, these road users will be addressed in the later stage of the implementation program under the mass action approach.

6 Conclusion

BSP is an internationally recognised practice for reducing traffic accidents. The systematic use of this program has been successfully carried out in many countries. It is hoped that, with the implementation of BSP, road safety on Singapore's roads should improve significantly. The Singapore BSP has capitalised on the advantages of international good practice to formulate local initiatives that complement the cultural driving behaviour.

If a BSP is to be successfully implemented, it is important that there is a reliable accident database so that problematic locations can be identified, problems diagnosed and the most appropriate treatments identified. The use of an unreliable database could lead to an unnecessary wastage of resources. The effort to identify locations will be reduced significantly if accident analysis software is used to help in the identification.

The purpose of this paper was to discuss the Singapore BSP and to present some initial findings. Preliminary before-and-after studies show positive results for most of the junctions. However, as the post-treatment duration has not reached the threshold of three years for the results to be statistically significant, no firm conclusions can be drawn at this stage.

It is envisaged that the successful implementation of BSP will lead to a reduction of number of black spot sites. As the number of black spot sites reduces, it should be possible to lower the threshold to the definition of a black spot. The criteria will be reviewed annually to take account of any changes in travel behaviour, enforcement, policies, etc. that could affect the type and frequency of accidents.

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Development of a Decay Curve for Pavement Marking Retroreflectivity

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ABSTRACT

The performance of retroreflectivity varies according to traffic volume age, the type of pavement marking material and its colour. Data collected on freeways throughout Korea was used to develop regression equations relating traffic volume and service life as independent variables and retroreflectivity as the dependent variables. This paper presents the results of the study, including a literature review of previous work in this area. The decay models developed were significant within the 90% confidence level and showed that there was a clear relationship with field data according to increase in cumulative vehicle exposure. Accordingly, these models can be used to determine service lives, retroreflectivity degradation rates, and retroreflectivity of new markings. It is recommended that aspects of pavement marking performance other than retroreflectivity, such as wear and adhesion to the pavement surface, also be considered when determining if a linemaking should be replaced.

1 Introduction

The performance of retroreflectivity varies according to traffic volume, the type and age of the pavement marking material and its colour. Data collected from freeways throughout Korea was used to develop regression equations relating traffic volume and service life as independent variables and retroreflectivity as the dependent variables. This paper presents the results of the study, including a literature review of previous work in this area.

2 Literature Review

Lee and Oh (2003) conducted laboratory wearing tests using an accelerated loading simulator to examine the effect of traffic volume on the retroreflectivity of pavement markings. Lee and Oh (2005) reported that, under environmental field conditions, pavement marking retroreflectivity was relatively low on freeways ramps, other than at the main lines of freeways, and also that the retroreflectivity was relatively low on climbing lanes and sharply curved sections.

Migletz et al. (1999) reported the results of field measurements of pavement marking retroreflectivity at sites in 32 states of the USA, including the economic implications of particular threshold values for the replacement of pavement markings. It was concluded that the minimum pavement marking retroreflectivity level should be clearly identified because it is a minimum target value for satisfactory pavement retroreflectivity.

Thamizharasan et al. (2003) identified three basic trends in terms of the degradation, or decay, of retroreflectivity over time. The retroreflectivity for newly-placed pavement markings increases initially because glass beads become exposed after some amount of wear, and then peak before reducing over time as the pavement markings wear out. The retroreflectivity of older pavement markings is represented by a straight line and gradually decreases over time.

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Thamizharasan et al. also found that the rate of degradation appeared to be linear for readings larger than 50 or 60 mcd/m²/lux, a highly relevant finding given that, if a minimum retroreflectivity value of 100 mcd/m²/lux is adopted, then a linear model to predict retroreflectivity degradation of older established markings may be sufficient.

Studies by Thamizharazan et al. (2003), Migletz et al. (1999) and Lee, Maleck and Taylor (1999) have shown that winter maintenance activities, such as snowplowing, has a pronounced adverse effect on the retroreflectivity of pavement markings.

3 Research Approach

The purpose of this study was to develop retroreflectivity decay models using data collected on freeways throughout Korea, specifically a relationship between retroreflectivity traffic volume and service life as independent variables and retroreflectivities as dependent variables. These models will be used to determine service lives, retroreflectivity degradation rates, and the retroreflectivity of new markings. The parameters studied included:

- the colour of the pavement markings
- the exposure of the pavement markings to traffic and the traffic volume
- the pavement marking material, including conventional, durable, modified acrylic and waterborne.

3.1 Data Collection

Data was collected on several freeways in Korea - including the Kyonbu, Seohaean, Honam, Namhae, and Seoul ring freeway lines – every three months during 2005 and 2006. Data was collected over a total length of freeway of 2,200 km. The location of the test sites is shown in Figure 1.

The pavement marking targeted included yellow centerlines and left-single-broken lines in the right-hand lane, i.e. the lane often used by heavy vehicles and used most frequently by exit and entry vehicles. The pavement marking retroreflectivity data was obtained using Laserlux.

The database was constructed in two ways. Firstly, retroreflectivity data for the same marking type but from different sites was accumulated. Using this method, it was possible to obtain a great deal of retroreflectivity data for a specific material of different ages and exposure to traffic. The data were used to develop a decay model that represented the average degradation of retroreflectivity of that pavement marking type for a range of ages. Although pavement markings operate under different climatic conditions, it was assumed, when developing the decay model, that the effect of climatic was slight compared to the other factors.

Secondly, retroreflectivity data for the pavement marking on each site was accumulated. Since the total number of retroreflectivity readings at each site over the two years was six, it was sufficient to represent the variation in retroreflectivity of each marking during its life. The retroreflectivity decay model for each site was therefore represented by a separate model using six readings. These models were used to predict the service life of a particular type of pavement marking and the residual life of the existing pavement marking.

3.2 Development of Decay Model

Regression analysis was conducted by setting the retroreflectivities of the pavement markings as dependent variables and the age and traffic volume as independent variables. Age and traffic volume were combined as a single variable since they had a very high correlation each other.

$$\text{Cululative Vehicle Exposure (CVE)} = \text{Age ADT} / \text{number of lanes} / 100,000$$

Regression analysis was conducted using the following four models and conformity was verified:

linear model: $Y = a + bX$

exponential model: $Y = a \text{Exp}(bX)$

logarithmic model: $Y = a + b \ln(X)$

power model: $Y = a X^b$
 where Y = retroreflectivity of pavement marking
 X = Cumulative Vehicle Exposure



Figure 1: Schematic map of target freeways

After integrating all the field data into a single database, CVE was calculated by investigating the date the markings were installed and the traffic volume on each site. The regression analysis for each pavement marking material was executed separately. After representing the variation of retroreflectivity, and estimating regression curves using linear, exponential, logarithmic and power functions, the regression curve which had the highest coefficient of determination and the value similar to the last field measurement was accepted as the retroreflectivity decay model.

Figure 2 shows the regression curves for the conventional white linemarking on asphalt pavements. The coefficients of determination (CoD) ranged between 0.26 and 0.76. After a review of the logarithmic and power models that had the highest CoD values, the power model, which predicted the value closest to the last field measurement, was adopted as the retroreflectivity decay model.

Figure 3 shows the regression curves for the conventional yellow linemarking on asphalt pavements. The CoD values ranged between 0.53 and 0.72. After a review of the logarithmic and power models, which had the highest CoD values, the logarithmic model, which predicted the value closest to the last field measurement, was adopted as the retroreflectivity decay model.

Figure 4 shows the regression curves for the durable white linemarking on cement concrete pavements. The CoD values ranged between 0.48 and 0.78. After a review of the logarithmic and power models, which had the highest CoD vales, the logarithmic model, which pedicted the value closest to the last field measurement, was adopted as the retroreflectivity decay model.

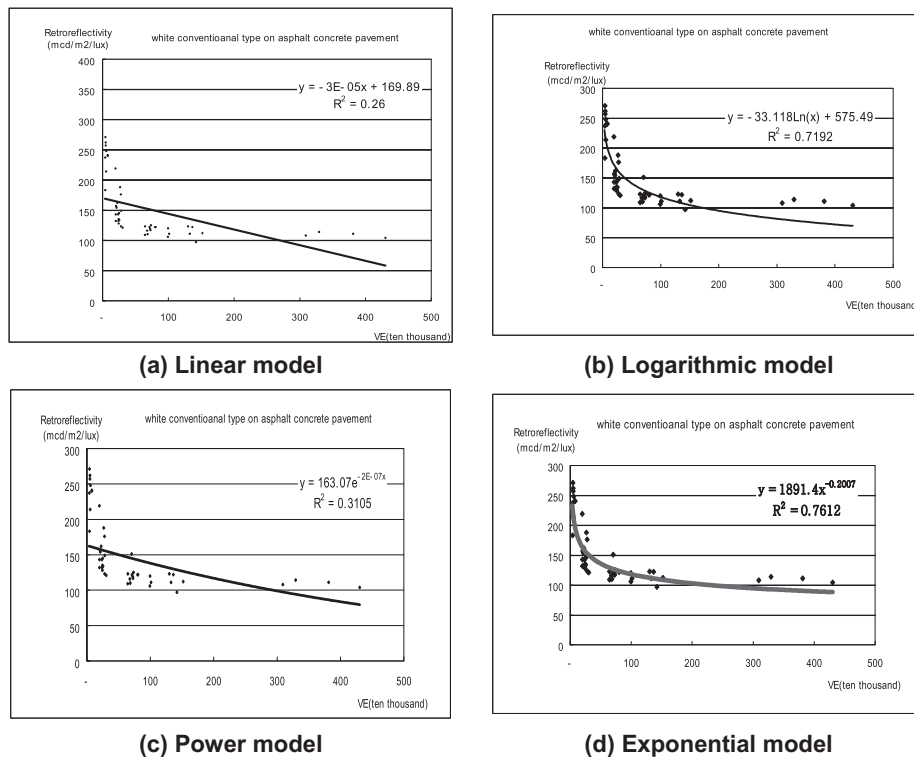


Figure 2: Regression curve for white conventional linemarking on asphalt

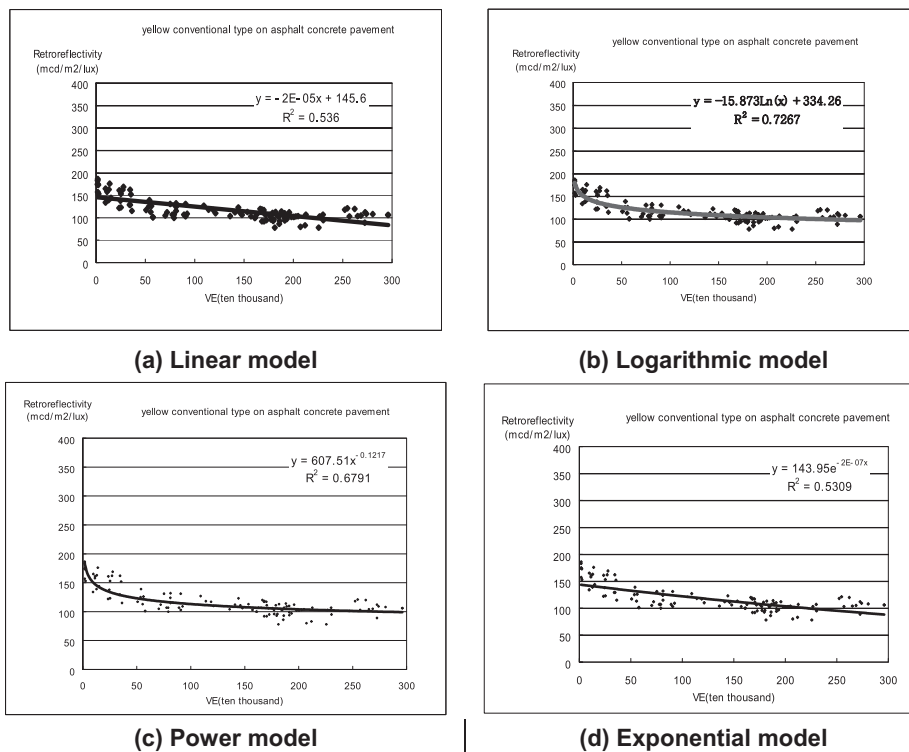


Figure 3: Regression curve for yellow conventional linemarking on asphalt

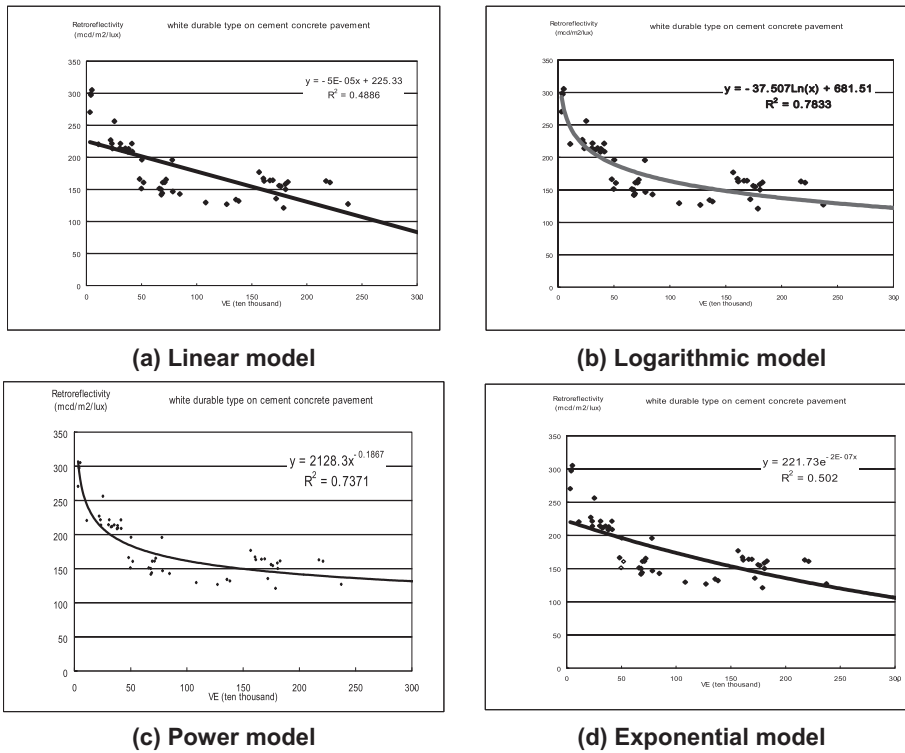


Figure 4: Regression curve for durable white linemarking on cement concrete pavements

Table 1 presents the predicted life for each linemarking type. The life is expressed as the Cumulative Vehicle Exposure, or the elapsed time for which the marking can maintain the minimum retroreflectivity values from the installation. For example, as the minimum retroreflectivity value for the white marking is 150 mcd/m²/lux, the predicted life (CVE) of the conventional white linemarking on asphalt pavements is 304,950, i.e. Y = 150 and X = 304,950 in the retroreflectivity decay model. Consequently, if the ADT is 5,000, then the estimated elapsed time is 61 days (304,950 divided by 5,000).

Table 1: Predicted Life of Each Linemarking Type

Material Type	Retroreflectivity Decay Model	Predicted Life (CVE)
Conventional white, asphalt pavement	$Y = 1891.4 X^{-0.2007}$	304,950
Conventional yellow, asphalt pavement	$Y = -15.873\ln(x) + 334.26$	1,367,362
Durable white, cement concrete pavement	$Y = -37.507\ln(x) + 681.51$	1,426,814

Table 2 presents the estimated durability of the conventional white pavement markings on asphalt pavements, according to traffic volume, using the linear model and the power model. As shown in Table 2 and Figure 5, the estimated durability varied according to traffic volume. On the site where the ADT was about 5,000, the estimated durability of the markings could be preserved for more than a year. However, on the site where ADT was about 20,000, the estimated durability dropped to the minimum retroreflectivity value after only four months.

The regression equations calculated for the linemarkings at each site are presented in Table 3. Applying this method, it was possible to develop the decay models for markings on each site which reflected local features. The decay models for each colour, pavement type, material and traffic volume may be used to predict the residual performance of the linemarkings at each site.

Table 2: Estimated Durability of Conventional White Linemarking on Asphalt

Traffic Volume (vehicles/lane)	Age (month)	CVE (10 ⁵ vehicles/day)	Retroreflectivity (mcd/m ² /lx)		
			Linear Model	Power Model	Average
5,000	0	0	251	278	265
	1	2	242	262	252
	2	3	233	247	240
	3	5	224	232	228
	9	14	170	162	166
	10	15	161	153	157
	11	17	152	144	148
	12	18	143	135	139
	13	20	133	127	130
	14	21	124	120	122
	15	23	115	113	114
10,000	0	0	251	278	265
	1	3	233	247	240
	2	6	215	219	217
	5	15	161	153	157
	6	18	142	135	130
	7	21	124	120	122
	8	24	103	106	106
	15,000	0	0	251	278
1		5	224	232	228
2		9	197	194	195
3		14	170	162	166
4		19	142	135	139
5		23	115	113	114
6		27	99	94	91
20,000	0	0	251	278	265
	1	6	215	219	217
	2	12	179	172	176
	3	18	142	135	139
	4	24	106	106	106
	5	30	70	84	77

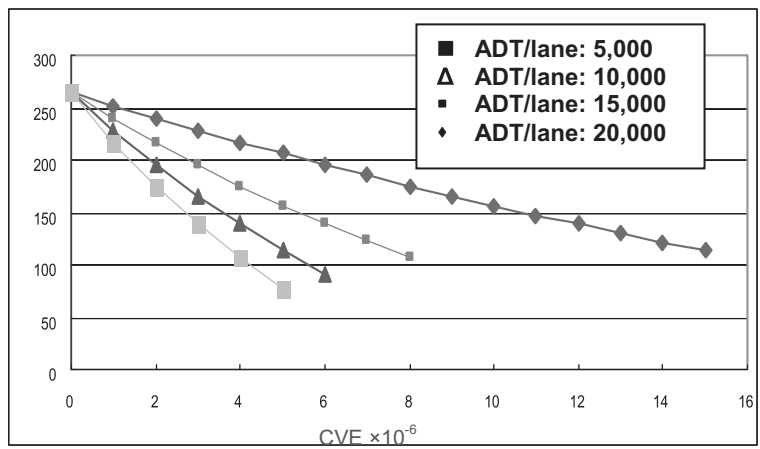


Figure 5: Estimated durability according to traffic volume

Table 3: Regression Equations for Each Site

Classification		Retroreflectivity Decay Model	Coefficient of Determination (R ²)	
Colour	white	$Y = -68.92\ln(X) + 153.51$	0.9947	
	yellow	$Y = -43.19\ln(X) + 113.82$	0.9823	
Pavement	white	asphalt	$Y = -62.88\ln(X) + 138.96$	0.9966
		concrete	$Y = -73.58\ln(X) + 168.71$	0.9910
		SMA	$Y = -66.61\ln(X) + 153.92$	0.9874
	yellow	asphalt	$Y = -40.45\ln(X) + 106.13$	0.9777
		concrete	$Y = -48.68\ln(X) + 112.18$	0.9870
		SMA	$Y = -39.71\ln(X) + 117.30$	0.9857
Linemarking Material	white	conventional	$Y = -55.01\ln(X) + 127.45$	0.9951
		durable	$Y = -71.83\ln(X) + 163.07$	0.9874
		water-borne	$Y = -87.17\ln(X) + 258.16$	0.9849
		modified acrylic	$Y = -68.81\ln(X) + 153.42$	0.9882
	yellow	conventional	$Y = -46.31\ln(X) + 118.79$	0.9928
		durable	$Y = -446.78\ln(X) + 111.41$	0.9973
water-borne		$Y = -37.03\ln(X) + 104.42$	0.9011	
Traffic Volume (ADT)	white	5,000~10,000	$Y = -59.41\ln(X) + 134.45$	0.9967
		10,000~15,000	$Y = -68.37\ln(X) + 159.32$	0.9942
		15,000~20,000	$Y = -77.95\ln(X) + 169.18$	0.9839
		20,000~25,000	$Y = -75.33\ln(X) + 153.35$	0.9876
		> 25,000	$Y = -135.26\ln(X) + 246.49$	0.9765

A comparison of the predicted and measurement retroreflectivity values of the conventional linemarking type on asphalt pavements is presented in Figure 6. The predicted values were calculated using the performance decay model whilst the measured values were collected in the field one year since the installation of the linemarkings. As shown in the Figure, values predicted by the performance decay models approximated the measured values.

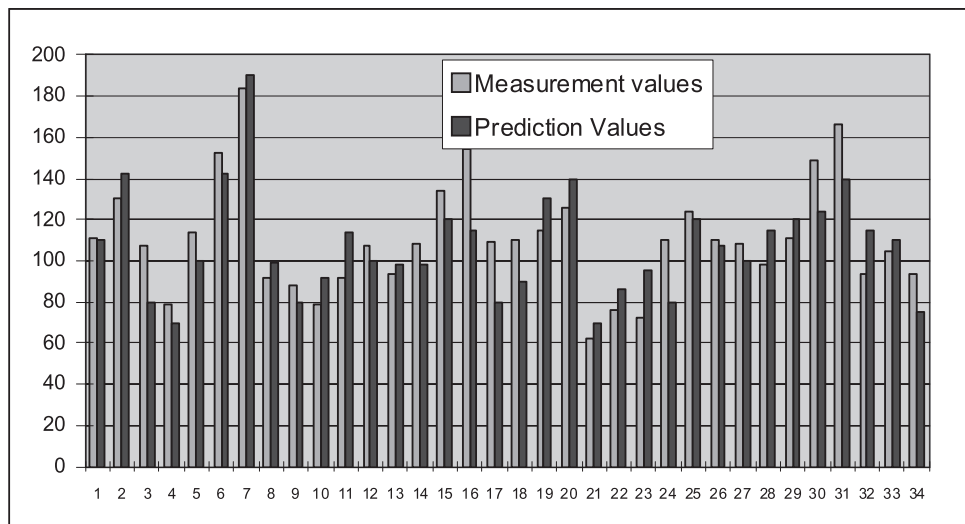


Figure 6: Comparison between prediction values and measured values

4 Conclusions

The performance of retroreflectivity varies according to traffic volume age, the type of pavement marking material and its colour. Data collected on freeways throughout Korea was used to develop performance decay models relating traffic volume and service life as independent variables and retroreflectivity as the dependent variables. This paper presents the results of the study, including a literature review of previous work in this area.

The models were first developed considering the factors affecting the performance of pavement markings. A logarithmic model was found to be appropriate to the field data with coefficients of determination values ranging from approximately 0.90-0.99.

Models were then developed considering traffic volume and age of the linemarking. The performance decay model for each material on the specific site was developed. The logarithmic model or power model were found to be the most appropriate, with coefficients of determination values ranging from approximately 0.72-0.78. The residual performance to maintain the minimum retroreflectivity was 1,429,989 vehicles for the conventional white linemarking on asphalt pavements, 4,820,535 vehicles for the conventional yellow linemarking on asphalt pavements and 4,145,037 for the durable white linemarking. Applying traffic volumes to a specific site, the residual time to maintain the minimum retroreflectivity can be calculated using these models.

Maintenance activities such as snowplowing and re-marking influenced the retroreflectivity results significantly and this had to be taken into account when developing the models.

The findings of this study may prove especially useful to highway agencies that rarely implement snow-plowing activities. It is recommended that aspects of pavement marking performance other than retroreflectivity, such as wear and adhesion to the pavement surface, also be considered when determining if a linemarking should be replaced.

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