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UNDERGRADUATE THESIS

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STATEMENT OF AUTHORSHIP

This thesis is the result of my own work,and all sources quoted or referenced have been stated correctly as they should be

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ABSTRACT

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The objective of the study was to identify the freeway systems performance especially the productivity of a freeway. The study relates literature review to the Australian National Performance Indicators (NPI) that has been proposed by Austroads and its verification with Speed-Flow Curves for Basic Freeway Segments of Highway Capacity Manual 2000. The study found that the productivity measurement by using NPI method did not mention any clear limitations and the values did not reflect the productivity of a freeway well. Furthermore, this study on Speed-Flow Curves for Basic Freeway Segments of HCM 2000 also suggested a set of values of optimum speed and flow that were believed more suitable than the normalisation values suggested by Austroads.

KEY WORDS

Freeway, Highway, Capacity, Freeway Performance, Productivity, Performance Measurement.

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CHAPTER 1

INTRODUCTION

The use of freeways to satisfy the increasing demand of transport has been growing in recent years. The travel vehicle in 2020 is expected to increase by about 31% compared to estimated capital city population growth of 15.9% in this period (Wright, Carl and Luk 2006). This demand growth is contributed by various factors such as Economic growth, Structural changes in the economy, Income growth, Working age, Employment growth and Public transport availability and service quality.

However, increasing demands will come with some issues on freeways such as congestion, safety, and environmental issues. These issues should be monitored and managed properly to achieve the maximum efficiency and productivity. The way to measure the level of congestion, safety and environmental issue in freeway is normally found by Freeway Systems Performance. The performance measurement process will start from collecting the data by using automated tools until the result comes out in the understandable way for either the decision maker or society.

There are three main aspects that are typically measured in freeway performance: (1) Mobility Performance, (2) Safety Performance, and (3) Environmental. These aspects will be discussed more in Section 2.

Background on Freeway Systems Performance Measurement

As briefly mentioned before, if the number of demand is increasing but the capacity remains the same, naturally there will be problems raised. Congestion is one of the example problems that are faced by engineers and transport planners for many years due to the increasing demand. Congestion itself could reduce the efficiency and productivity of freeway. Therefore, the traffic condition in a freeway should be monitored and managed to get the maximum efficiency and productivity of a freeway by implementing freeway systems performance measurement.

The actual condition of a freeway is captured by measurement tools that will be discussed more in Section 2.2. This data will be analysed to get the level of congestion or other indicators that are usually used in measuring freeway performance. Once the performance is analysed and the output is produced, then the output is used to get more research on how to increase the efficiency and productivity or reducing the congestion or the crash rate in freeway. At this stage, freeway systems performance measurement gives much contribution on the freeway improvement and consideration for transport planning.

As can be noted from Margiotta et al. (2006), in United States, freeway systems performance is used by some audiences that can be seen in the following table:

Intended Audience Typical Interests	**Intended Audience Typical Interests**
Operations personnel (particularly those associated with Traffic Management Centers (TMC) and state wide coordination of operations activities)	Identifying successful/unsuccessful operations programs and where/when to alter specific operations programs.
Designers	Identifying geometric constraints.
Programming personnel	Identifying necessary improvement projects.
State and Metropolitan Planning Organisation (MPO) transportation planners	Identifying how well system is performing and ensuring regional and/or business plans are satisfied.
Federal Highway Administration (FHWA)	Identify how national and state wide roadway networks are performing and to assist in Federal allocation of funding to needed projects.
Academia	Academia Improve data sources and/or estimation procedures.

Legislators and other funding/policy decision-makers	Accountability – Ensure citizens they represent are receiving a good system for the dollars being spent
Media	Accountability – Broadcasting successes, failures, and possible opportunities.
Agency oversight and accountability commissioners or boards	Accountability – Ensuring a benefit to funded programs and to what extent funded programs are successful

Table 1 Typical Audiences Along with Associated Interest

From Table 1 of each typical interest of audience, it can be summarized that there are three main reasons why freeway performance measurement are needed:

- To ensure the highest level of transportation service by understanding what travel conditions are like and how they are changing (customer focus);
- Accountability; and
- Public relations

1.1 Aim

The aim of this research project is to:

- Give a picture of what indicators are needed in freeway systems performance measurement
- Illustrate how the data is collected
- Show the method of how performance of freeway can be measured
- Investigate one freeway systems performance measurement

1.2 Objective

Further specific objective of this research project that can be seen in the analysis is to:

- Investigate one freeway systems performance analysis method that is currently used, and one of the indicators that is believed can reflect the performance of a freeway
- Evaluate the method and indicator by comparing with Highway Capacity Manual 2000
- Criticise the findings from the analysis and study
- Give suggestions on the method and the productivity measurement

CHAPTER 2
LITERATURE REVIEW

2.1 Performance Indicators

2.1.1 Mobility Performance

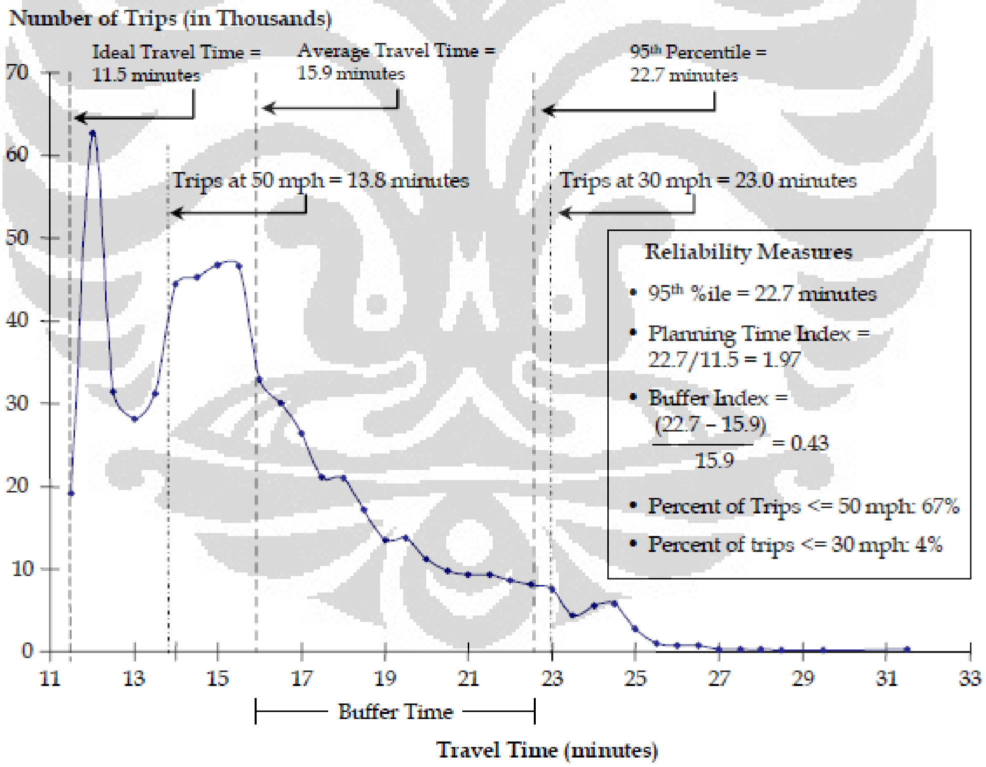
Mobility is one of the most important aspects that should be controlled and measured regularly in traffic engineering. Since mobility is defined as movement of people or goods, therefore the mobility performance can be described as measurement of how well users can complete the entire trips by considering some basic parameters such as travel times, delay, road level of service, and cost per person-trip. Moreover, the nature of roadway events that contribute to delay the traffic flow also includes i.e. incidents, weather, and work zones. (Margiotta et al. 2006)The output of mobility performance is a report that gives the idea to traffic operators or the decision makers about the actual traffic condition of the freeway that sometimes includes the congestion.

The data collection of basic parameters needs to be accurate and efficient; therefore methods and tools are developed to support data collection and analysis. Rapid growth in technology especially in the last few decades has made a massive development in tools for collecting, managing and analysing data. The use of technology in transportation systems are known as Intelligent Transportation Systems (ITS) which has already been used in Australia. ITS can be used from data collection until traffic enforcement (i.e. speed camera, bus lane camera, etc). Furthermore, one of the systems that can be used as the example in measuring the freeway performance is freeway performance measurement systems (PeMS) that has been used and developed in California, United States.

2.2.1.1 Travel Time

In definition, travel time is the average time consumed by vehicles traversing a fixed distance of freeway. Usually, travel time is measured in minutes and at a particular point on a section or representative trip. The time scale for travel time measurement is a whole day which includes the peak hours of a.m. p.m. and midday. Moreover, from the travel time, the travel time index can be calculated by comparing the actual travel rate to the ideal travel rate or ratio of travel time in peak hour vs. free-flow travel time.

Nowadays, the travel time is an issue for public and business sector (Margiotta et al. 2006). How consistent travel conditions are from day-to-day, which is also referred to as travel time reliability, this is one of the problems that is related to congestion. The reliability can also be measured from the probability or occurrence of failure in terms of travel times e.g. percent of trips that occur at half the free flow speed. Reliability becomes an issue because travel times could be unreliable when some delaying events take place in a freeway. The relationship between travel time and travel time reliability can be seen in Figure 1.



Source: National Cooperative Highway Research ProgramGuide to Effective Freeway Performance MeasurementFinal Report and Guidebook (2006)

Figure 1Travel Time Reliability Is Determined by the Distribution of Travel Times and Related Reliability Measures, SR 520 Seattle, Eastbound, 4:00-7:00 P.M. Weekdays (11.5 Miles Long), January–April 2004

Travel time has been identified by Austroads as an important system performance measure (Austroads 1997). It is also important for travellers, operators and planners point of view. Travellers need the specific information about their trip, because freeway traffic conditions are never the same from day-to-day,these variations can be caused by bad weather, traffic incident, or due to work zones that may be in place for a period of time. Operators have similar point of views as travellers; operators want to know the systems performance at the present time in relation to normal conditions. Moreover, planners want to know how the travel time changes over a certain period of time i.e. the travel times and freeway performance in last month and/or last year whether the condition is getting worse or better. Furthermore, these comparisons will come as one of their considerations for future developments and decisions.

2.1.1.2 Total Delay

Definition of total delay is "*the excess travel time used on a trip, facility, or freeway segment beyond what would occur under ideal conditions*" (Margiotta et al. 2006). The ideal condition is the unconstrained freeway conditions under free flow speed. Moreover, total delay has a close relationship with congestion since the total delay is one of the parameters measured in the congestion analysis.

There are two units in total delay: person-hour and vehicle-hours, those units are for Person Total delay and Vehicle total delay respectively. The derivation of total delay is delay per vehicle which is the total delay in the freeway divided by the number of vehicle using the freeway; the unit is Hours (vehicle hours per vehicle). Besides those core aspects in delay measurement (total delays and delay per vehicle), there are some supplemental and more detailed aspects for freeway performance measures e.g. (1) Bottleneck ("Recurring") Delay, (2) Incident Delay, (3) Work Zone Delay, (4) Weather Delay, (5) Ramp delay (where ramp metering exists) that occurs at ramp meters, and (6) Abnormal Volume-Related Delay that measures delay caused by abnormal high volumes (Margiotta et al. 2006).

2.1.1.3 Throughput Vehicles

Throughput measurement is a measurement of the number of users being served by the freeway systems in a period of time e.g. in an hour or a day. The throughput measurement can be applied either to the passage of persons or vehicles. The degree of how the facility is operating can be measured by vehicle-based measurement and the capability of comparing different modes, including the high-occupancy vehicles or transit lanes can be measured by person-based vehicle. Person-based measures can be obtained by converting from vehicle-based measure to person-based, which is done by multiplying the number of vehicle with either actual or average vehicle occupancy rate. (Margiotta et al. 2006)

Furthermore, both vehicle-based and person-based measurement should be done in order to get more detailed data. However, the throughput measure alone does not show the characteristics of a freeway system itself, they are very useful as supplemental and explanatory measures (Margiotta et al. 2006). Besides, vehicle-miles of travel and truck vehicle-miles of travel are other measurement forms that can be used to measure the throughput in freeway systems. The vehicle-miles of travel is basically the product of the number of vehicles travelling over a length of freeway, the vehicle term can be replaced by the number of trucks to get truck vehicle- miles of travel.

In addition, throughput measurement can be used in congestion measurement. Number of increased demand is one of the congestion major causes and this number can be measured by looking at the throughput value of freeway systems. As stated in National Cooperative Highway Research Program (NCHRP) (2006), vehicle-miles travel can also be used as a basis for constructing the crash rates, then it makes vehicle-miles travel which is also single most important measure of throughput. However, it does not give any further detail explanation.

2.1.1.4 Congestion

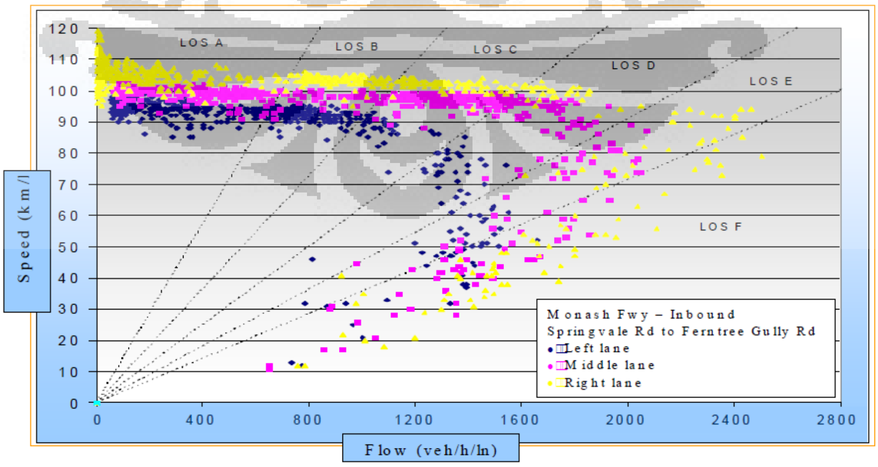
Congestion is defined in The United States Federal Highway Administration (FHWA) as “an excess of vehicles on a portion of roadway at a particular time resulting in speeds that are slower - sometimes much slower - than normal or ’free flow’ speeds”. In the simple explanation, congestion occurs when the demand exceeds the capacity and mostly exists during peak hours in urban areas. As the capacity is exceeded, then people try to add more freeway capacity or curtail the freeway travel time. The similar definitions also stated by Varaiya(2004). Varaiya said that congestion occurs when the operation of highway during high demand is not efficient. His analysis told us that the congestion reduces the efficiency by 20% to 50%; which also means 20% to 50% more time to travel a particular congested freeway segment.

Wright, Carl and Luk (2006) revealed the causes of the congestion, which are divided into two main causes; Recurring Causes of Congestion and Non-Recurring Causes of Congestion. Detail congestion causes include:

- Recurring Causes of Congestion
  - The traffic volumes at freeway section between the interchange is much more than the critical throughput capacity of freeway
  - Great volume entering the freeway will interfere the main flow
  - Vehicles moving in a short distance to exit ramps: Traffic queuing will block the left lane of the freeway or slows vehicle prior to exit ramp
  - Sudden movement of vehicle: trucks or slow vehicle are using multiple lanes and changing lane will make other vehicles breaking, last-minute lane changes
  - Vehicles turning from the outer lane and build flow disturbance and reducing the freeway which will lead to congestion
  - A lot of vehicles trying to use the freeway at the same time
- Non-Recurring Causes of Congestion
  - Accident and Breakdown
  - Extreme Weather condition (e.g. heavy rain, snow, and fog)
  - Maintenance or roadwork activities
  - Special events (i.e. Olympic Games or commonwealth games, any sporting events, etc)
  - Geometric features, such as upgrades, transitions from four to three lanes, width restrictions or tight curves

The unstable traffic flow conditions, as mentioned above can result in freeway traffic congestion and can develop when a freeway is operating at or near its design capacity. If this condition is applied to unmanaged freeways, it could make a sudden collapse in flow volume and speed, and the throughput drop to about 25% which will be extended for long period, then will finally lead to severe congestion. (Wright, Carl and Luk 2006) According to Wright, Carl and Luk study (2006), drivers began to slowdown slowly when the traffic volume exceeds about three quarters of design capacity, because it is an effort to restore an acceptable following distance. When traffic volume reaches design capacity, drivers are in high level of alertnesswhich changes the traffic flow.The flow becomes very vulnerable as drivers are more hesitant to change lanes, increase the use of their brakes and therefore collapse the freeway flow to less than 50% of design capacity. If this condition happens, the flow will remain at the reduced level for a long period, or traffic will stop momentarily for no reason and speed up for about 200 m before it stops again.

Figure 2 below shows the effect of collapsing freeway on its volume and speed. It can be seen that the fast lane which has less interference is stable at 100km/hr until it reach the volume about 1800 veh/hr. However, the centre and outer lanes that has more traffic interference are less stable and collapse when reaching about 1000 veh/hr.



Source: VicRoads. Guidelines for Managing Freeway Operating With Ramp Metering, Nov 2005

Figure 2 Traffic Flow Breakdown

There is no standard measurement of congestion. Wright, Carl, Luk (2006, 5) argued that terms of percentage of time traffic dependson the various level of service or volume versus capacity which are usually used by engineers to rank the traffic density and speed. Moreover, the terms of delays per traveller, travel time variability and speed are usually used by freeway users to measure the level of congestion; tools to measure these terms will be discussed in the following sub-chapter. The economists are looking for cost issues; they believe that there is another 'optimal' level of congestion that should be kept, in which some road users either, postpone their trips to another day, do not travel at all, travel in off peak hours, and usepublic transport or ride-share.

Bottleneck Theory

Traffic bottleneck is the condition of a localized disruption of vehicular traffic on a street, road or freeway. The bottleneck condition is often temporary and more due to the physical condition of the road or freeway itself. Varaiya (2002, 9) stated that bottleneck study location can be determined by analysing speed contour maps; the speed contour map can be obtained by implementing intelligent transportation systems, especially loop detectors for his research.

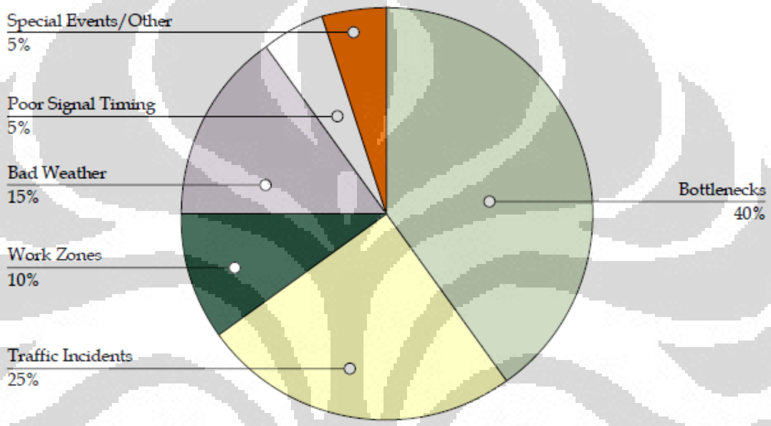
NCHRP (2006) stated that there are two categories identified to give effects on bottleneck congestion:

- Geometric Deficiencies Related to Traffic Flow. The geometric areas that gives more possibilities to have bottleneck congestion if the demand volumes are quite high. The bottleneck types are:
    - Types A-C weaving areas (see HCM and Section 7.0);
    - Left-hand exits;
    - Freeway-to-freeway merge areas;
    - Surface street on-ramp merge areas;
    - Acceleration lanes at merge areas < 300 feet;
    - Lane drops;
    - Lane width drops ≥ 1 foot;
    - Directional miles with left shoulders < 6 feet;

- Directional miles with right shoulders < 6 feet;
- Steep grades; and
- Substandard horizontal curves.

- Major Traffic-Influencing Bottlenecks. In urban areas, this condition is usually applied in freeway-to-freeway interchange or because of lane-drop exists.

Based on NCHRP (2006), bottleneck acts as the major causes in U.S. freeway congestion, as shown in Figure 3.



Source: NCHRP Guide to Effective Freeway Performance Measurement Final Report and Guidebook (2006)

Figure 3 Sources of Congestion in U.S. Freeway

2.1.1.5 Productivity

Productivity is one of the indicators that measures efficiency of freeways and one of six traffic systems that is included in the Australian National Performance Indicators. This indicator is very useful in managing freeways, since it indicates to the freeway's managers that the freeways are in fully functioned condition and also indicates the satisfaction of travel experience for individual road users (the speed is above normalisation speed or not).

It can be noted that productivity is actually a product of speed and flow. Somers (2010) stated equation regarding productivity as shown in below:

$Productivity\ = \frac{speed \times flow \times 100\%}{speed_{\ norm} \times flow_{\ norm}}$ This equation applied for speed <normalisation speed

= 100. This Number applied for speed ≥ normalisation speed.

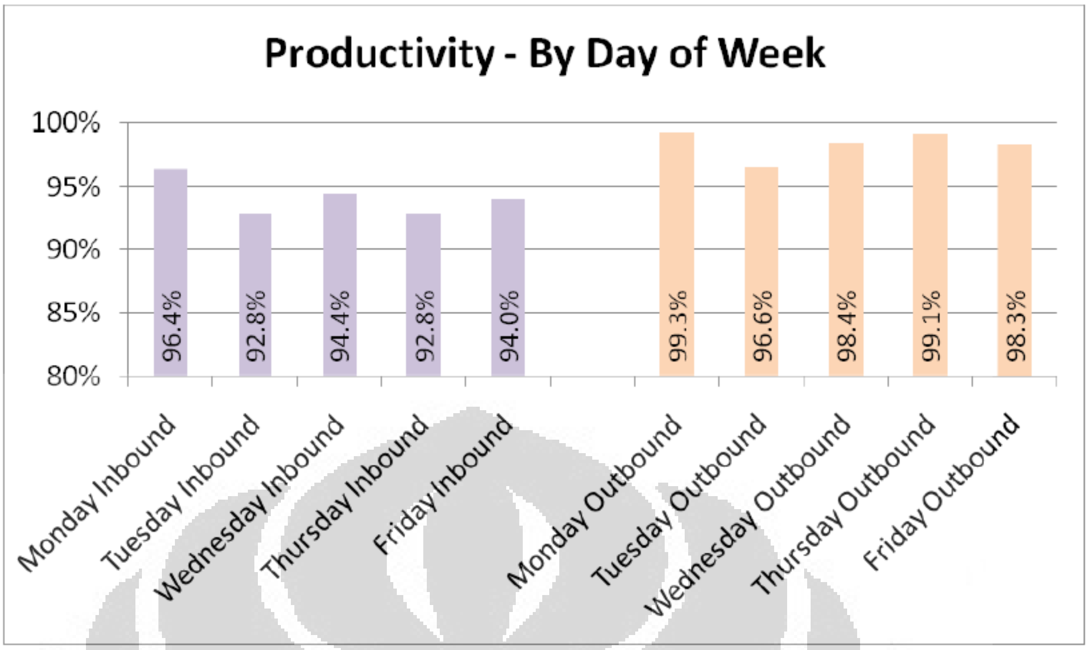
Equation 1 Productivity Equation

The recommendation of normalisation speed for freeway is to be set at 80 km/h and normalisation flow rate is at 2000 pc/h/lane.

Normalisation Speed

Normalisation speed controls the productivity indicator. When travel speed is above normalisation speed, the productivity will reach 100% which means full regardless of traffic flow. The full productivity also cannot be reached if the traffic flow is less than normalisation traffic flow. If the traffic flow is less than normalisation traffic flow, then freeway performance still cannot represent to be degraded if all of the demand has been satisfied with an acceptable speed level. In short, the degraded productivity will not be reported if there is still spare capacity.

The use of 80km/h is not appropriate to manage freeways since the variable speed limit may be applied to maximise flow during peak periods. Selection of 65 km/h of normalisation speed for managed freeway is suggested by Somers (2010). Somers (2010) further explained that in case if road users travel within legal speed limit, the freeway will show less than 100% productivity at the time where there is spare capacity. This will cause the degraded productivity to be reported at these times as a false positive reading. One of the examples that Somers and George (2010) has done in measuring the productivity can be seen in Figure 4 overleaf.



Source: Network Operating Plans and Performance Targets (2010)

Figure 4 Productivity on Monash Freeway (Wellington Road to Toorak Road)

2.1.1.6 Reliability

Similar to productivity measurement, reliability measurement also measures the efficiency of a freeway. This indicator measures the variability of speed within a freeway in a period of time. Thus, it shows the proportion of road network at different levels of variability in a measurement time period (Somers 2010). Somers also argued that this indicator is best available for determining whether the freeway performance was in line with road users' expectations for that time of day, based on variance from previous traffic conditions for that section of the road and time of day.

It can be noted from Somers 2010 that equation for reliability (travel speed) indicator is shown as below:

$$\text{Reliability } (r,t) = \frac{1.44}{AS_{r,t}}\sqrt{\frac{\sum_{d}\left(S_{i,r,d} - AS_{r,t}\right)^2}{N_{r,t} - 1}}$$

Where $AS_{r,t} = \frac{\sum_{d} S_{r,t,d}}{N_{r,t}}$

Equation 2 Reliability Equation

$AS_{r,t}$ is the average speed of all of vehicles on route *r* in time *t* (15 min interval), averaged over all days *d*

$N_{r,t}$ is the number of days that speed values on route *r* are obtained at time *t*

$S_{r,t,d}$ is the speed averaged over all vehicles on route *r* at the time *t* and on day *d*

Further, Somers (2010) identified three values for consideration as potential thresholds: 0.2, 0.4, and 0.6. In order to ease the way of communicating the performance measured, it is proposed to assign plain English wording to the thresholds as follows:

- 0.2 represents "Very Low Variability in travel times"
- 0.4 represents "Low variability in travel times"
- 0.6 represents "Moderate variability in travel times"

Table 2 and Table 3 represent the Reliability for peak period and off-peak period respectively of inbound direction between Warrigal Road and Toorak Road.

Peak Period (6-10am, 3-7pm)		
Austroads Reliability Value	**Preliminary Performance Target**	**Measured Performance**
0.2 (very low variability)	(not specified)	55%
0.4 (low variability)	80%	69%
0.6 (moderate variability)	95%	86%

Table 2 Peak Period Reliability – Inbound Warrigal Road to Toorak Road

Outside Peak Period (other times)		
Austroads Reliability Value	Preliminary Performance Target	Measured Performance
0.2 (very low variability)	80%	96%
0.4 (low variability)	95%	99.8%
0.6 (moderate variability)	(not specified)	100%

Table 3 Reliability outside peak periods – inbound Warrigal Road to Toorak Road

2.1.1.7 Australian National Performance Indicators

Australian National Performance Indicators (NPI) has established a set of standard indicators that can be used in measuring the performance of a road or freeway that will be used by road authorities (Somers 2010). Traffic systems, that include travel speed, delay, and variability, are one of the six NPI categories.

As can be noted in Somers (2010), there are five indicators that are set out by Austroads for Network operations, as listed below:

- Traveller efficiency (Travel Speed)
  It monitors the congestion in terms of speed. On freeways the speed can be derived directly using point sensors such as a pair of loops.
- Traveller Efficiency (Variation from Posted Speeds)
  This indicator monitors the proportion of an arterial road network at various levels of deviation from posted speed limits on freeway
- Traveller Efficiency (Arterial Intersection Performance)
  This indicator monitors the proportion of the level of congestion based on degree of saturation and the ratio of actual volume.
- Reliability (Travel Speed)
  As discussed in previous chapter, this indicator measures the variety of speeds by calculating the coefficient of variation.
- Productivity (Speed and Flow)
  It measures the efficiency of a freeway by multiplying the speed and flow. More detail of productivity has been discussed in Section 2.1.1.5.

2.1.2 Safety Performance

Safety performance is one of the parameters that should be measured in order to get full measurement of freeway systems performance. Freeway safety performance is closely related to road safety engineering issues. Moreover, comparing mobility and performance measurement, a slight difference in approach is used to measure the safety measurement of a freeway. Road safety is mostly discussed in Austroads Guide to Road Safety (AGRS) and Austroads Guide to Traffic Management (AGTM) especially AGTM Part 13: Road Environment Safety. Besides, other reference from European theory and manual about road safety performance can be found in "Road Safety Performance Indicators Theory (2007)" and "Road Safety Performance Indicators Manual (2007)".

According to Margiotta et al. (2006), number of crashes, type of crashes, and level of severity should be measured. In addition with secondary crashes which means crashes that occur in because of, or influenced by, a previous crash should also be measured as an input of analysing freeway performance. Similar measurement also mentioned in AGRS Part 1: Road Safety Overview (2009), such as:

- Number of crashes or numbers of deaths and injuries
  The crash rate should be broken down into some crash fatality classification, e.g. fatal or serious injury, other injury and non-injury. Number of death measured can lead to some reasons and will analyse other indicators such as the effectiveness of using safety helmets, using safety belt, etc. Moreover, number of death measured also sensitive for the media issues and politicians concern.
- Deaths and injuries per 100,000 population
  It represents the number of safety on a particular population. This could also be related to other form of injuries and death which are useful when considering overall impact of road safety programs.
- Deaths and injuries per vehicle kilometres travelled (VKT)

This measurement measures the level of safety for travelling vehicle, especially when relative issue for different classes of road user, types of vehicle, or different types of road are considered.

- Deaths and injuries per 10,000 registered vehicles
  This is a measurement of deaths and injuries per unit of travel, the number of vehicle on register is more available to get when data on vehicle use may not be available. The advantage of this measurement is limited to be used in analyses of traffic system performance.
- Deaths and injuries per hours travel or per trip
  It provides another point of view on travel safety. It can be noted from AGRS Part 1 that rates are expressed as injuries or death per 10 trips.

Safety performance indicators are defined by European Transport Safety Council (ETSC) 2001 as "*measurement that is causally related to crashes or injuries, used in addition to a count of crashes or injuries, in order to indicate safety performance or understand the process that leads to accidents*".

The assessment of freeway safety in terms of accidents and injuries is the most common indicator. However, only showing the number of crashes or injuries is often not a perfect indicator that reflects the freeway safety performance (Hakkert, Gitelman and Vis 2007). They argued that measuring the safety performance from the crashes and accidents are correct,however it will only measure freeway performance at the very worst case condition. At the same time, road safety analysts and policy makers are looking for many other factors to be considered in order to achieve more detail and a higher level of safety that can be controlled. The additional information, parameters or indicators provides a means for monitoring the effectiveness of applied safety actions.

The reasons of safety performance indicators (SPI) are needed in safety performance measurement, which is given below:

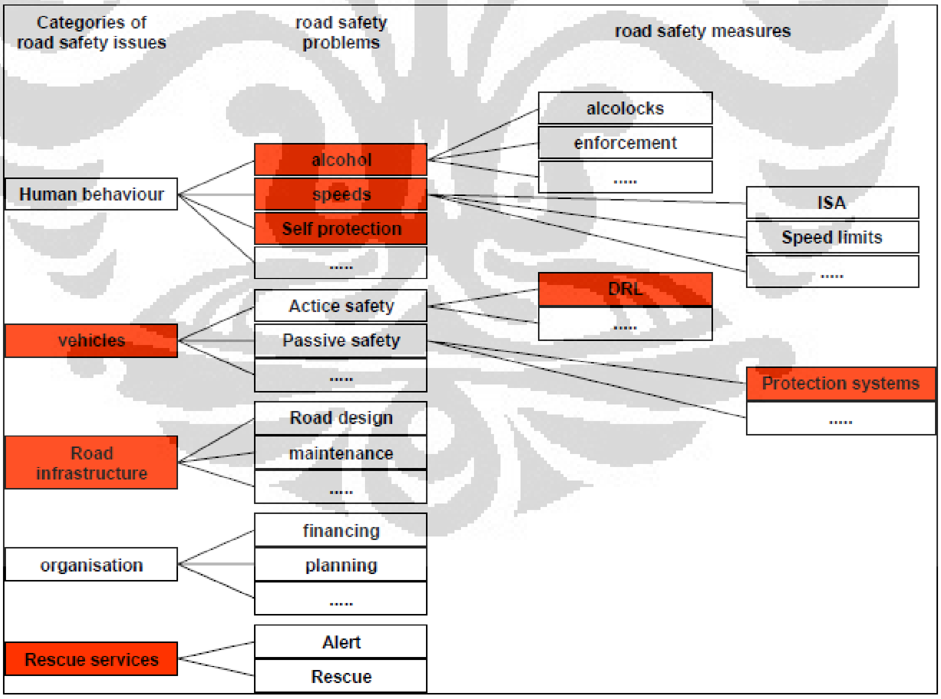
- There is a random fluctuation in number of crashes and injuries
- Incomplete report of crashes and injuries in official road accident statistics

- Counting number of crashes does not give any information about the crashes reasons
- Understanding of process that lead to accidents is needed in order to develop the effective measures to reduce number of accidents or injuries

Some of Indicators that were mentioned both in Road Safety Performance Indicators Manual (2007) and AGRS 2009 are:

- Alcohol and Drugs
- Speeds
- Protective systems

Indicators and other parameters in freeway performance measurement can be summarized into Figure 5 below. Figure 5displays what aspects or indicators should be measured during freeway safety performance. The highlighted boxes are recommended by Hakkert, Gitelman and Vis 2007.



Source: Road Safety Performance Indicators Theory (2007)

Figure 5Suggestion for Freeway Safety Performance Measurement Indicators

2.1.3 Environmental

The environment is a major concern in societies, and transport is a major source of environmental damage. Therefore, it should not be surprising if environmental analysis has played an important role in measuring freeway systems performance. There are some impacts that can be considered when analysing environmental performance of highway. Those impacts can be classified into natural impact, physical impact and social impact. Another analysis that can be put into the environmental analysis consideration is fuel consumption analysis.

Tools and techniques that are used in measuring the environmental impacts of freewaysare different to the mobility and safety measurement tools. As in environmental performance measurement, mostly chemical substances is the aspect that will be measured, therefore it needs tools and techniques to measure levels of those chemical substances, rather than number of vehicle passing a freeway or average speed in a freeway.

Section 2.2 will discusswhich tools are used in measuring freeway performance and are limited to mobility and safety performance. Environmental performance tools and techniques will be discussed more in environmental engineering or environmental science areas that will not covered in this thesis.

2.1.3.1 Natural Impact

Potential negative impacts on natural component such as biological systems near the transportation facilities (freeway) have been a major focus of environmental studies concerned with the natural system. The purpose of natural impact measurement on a freeway is to measure the ecological change or affected by the freeway. Even though the natural impact assessment should have been measured during planning stage, but the measurement is also needed to monitor the ecological condition along the freeway.

The quantitative measurement in freeway ecological condition can be determined from comparing current number of particular species in a location with the previous number which can be from last year data or the assessment data during planning stage (Petts 1999).

2.1.3.2 Physical Impact

This is a major concern of environmental impact assessment of freeway performance; this is due to the fact that impact measurement is closely related to number of vehicle travelling on a freeway. Physical impact is derived into two categories: Air pollution and Noise pollution.

2.2.3.2.1 Air Pollution

For many years, the relationship between transportation systems performance and air quality has become a major interest for engineers and transport planners (Meyer and Miller 2001). It can be noted that there is one model set that estimates the motor vehicle emissions by converting information from driving conditions, vehicle and driver behaviour, and environmental factor itself. This model is referred to as an emission model. This model can be used to measure levels of air pollution associated with freeway systems performance measurement.

According to Meyer and Miller (2001), there are some factors affecting the vehicle emission rates as can be seen in Table 4:

Vehicle Parameters	Vehicle Classification Model and year (weight engine size, etc) Accrued vehicle mileage Fuel delivery system Emission Control system
Fuel parameters	Fuel Type Oxygen content of fuel Fuel volatility Sulphur content Benzene content
Vehicle operating conditions	Average vehicle speed Trip length and number of trips per day Driver behaviour

Table 4Factors Affecting Vehicle Emission Rates

In more detail, as suggested by Margiotta et al. (2006), there are some chemical components that should be measured annually in order to get the pollution level in air and Petts (1999) mentioned the techniques to measure them. The suggested chemical measurement and the techniques can be summarized in following table:

Pollutant	Monitoring Technique
Nitrous Oxides (NOx) Emission Rate,	Diffusion Tube Chemiluminescence Christie Arsenite
Volatile Organic Compound (VOC) Emission Rate	Total hydrocarbon/non-methane hydrocarbon analyser Gas chromatography/ Chemiluminescence
Carbon Monoxide (CO) Emission Rate.	Infra-red absorption Electrochemical cell

Table 5Suggested Air Pollutant Measurement and The Technique

Six strategies that have been used to reduce the amount of pollutant emissions coming from on-road motor vehicles un U.S. mentioned by Meyer and Miller (2001), such as: (1) Reducing the emissions from new vehicles that displace older, high-emitting vehicles; (2) accelerating the vehicle fleet turn over to get the new vehicles into fleet more quickly; (3) reducing emissions from in-use vehicles through such strategies as vehicle inspection and maintenance strategies; (4) reducing travel demand to reducing vehicle activity; (5) improving traffic flow to reduce emission rates; and (6) use of low polluting alternative fuel.

2.2.3.2.2 Noise Pollution

The production of noise is one of the most apparent physical impacts of a transportation facility's operation including freeways. The exposure of high levels of noise over a period of time can have damaging effects on the physical and mental well being of humans. Another important characteristic of noise in terms of human hearing is sound intensity decreases with the square of the distance from a point source. The noise level will decrease either 3 or 4.5 dBA in the case of transportation facility. The noise level of transportation in urban areas can be seen in Figure 6.

Noise level (dBA)

Type and location		Individual reaction
Rocket engine	180	Pain threshold
Motorcycle at a few feet	110	Deafening
Loud auto horn at 10 ft	100	
Lawn mower	98	Vocal effort
Freight train	95	
Philadelphia rail car (underground)		
Station platform	93-98	Loud and very annoying
Inside cars	82-95	
Large truck at 50 ft		
Busy city street	90	
Toronto subway car		
Station platform	84	
Inside cars	78	Annoying
Philadelphia trolley car (above ground)		
Station platform	80-85	
Inside cars	65-75	
Highway traffic at 50 ft	70	Telephone difficult to use
Light car traffic at 50 ft	60	Intrusive
Normal breathing	10	Barely audible

Source: Urban Transportation Planning (2001)

Figure 6Transportation noise in urban areas

Noise is measured in decibel which is equivalent to "sound pressure level". For highway traffic and other noises, an adjustment, or weighing, of the high- and low-pitched sounds is made to approximate the way that an average person hears sounds. The adjusted sounds are called "A-weighted levels" (dBA). Freeway traffic noise is the largest single source of noise that is considered most frequently in an Environmental Impact Statement (Bregman and Mackenthun 2000). Bregman and Mackenthun also argued that the noise levels change with the number, type and speed of vehicles which produce it.

The dBA measure has frequency response characteristics that correlate to human impressions of loudness. The "A" filter reduces the intensity of low and very high frequency that human ears have lower sensitivity.

It can be noted from Meyer and Miller (2001) that the widely used measure of noise method is by using percent of time certain noise levels are exceeded during a specified time interval.

These common level including:

- L_{90} = noise level exceeded 90 percent of the time
- L_{50} = noise level exceeded 50 percent of the time
- L_{10} = noise level exceeded 10 percent of the time
- L_{dn} = noise level average over 24 hours
- L_{max} = highest sound level measured during a given period of time

However, the most common measure is called equivalent sound level which is denoted by L_{eq}, which represents the average energy level reaching an observer during a specified period of time. Further equation and explanation about measurement method will not be discussed in this report.

2.1.3.3Social Impact

The Socialimpact should be monitored in order to get the performance of a freeway. TheSocial impact measurement will measure the community quality of life. Moreover, social impact can also be referred to as community impact which can be defined as effects of freeway on neighbourhood or groups of neighbourhood (Meyer and Miller 2001). Moreover, the performance measurement method will also be different from the others.

The impact on the community can be seen on one of the factors such as the economic impact, which has a close relationship with highway productivity. It can also be noted that the measurement on freeway cost performance is also related to congestion which will increase the travel cost.

Social impacts can also be related to customer satisfaction measurement on freeways. Aspects that were suggested to be covered when measuring the customer satisfaction are: Worst Aspect of Freeway Congestion and Satisfaction with Time to Make Long-Distance Trips Using Freeways (Margiotta et al. 2006). Those two aspects can be measured by giving questionnaires.

The suggested units which can be used in measuring customer satisfaction:

- Worst Aspect of Freeway Congestion measurement: (1) happens every work day; (2) incidents that are not cleared in time; and (3) encountering work zones.
- Satisfaction with Time to Make Long-Distance Trips Using Freeways: (1) very satisfied; (2) somewhat satisfied; (3) neutral; (4) somewhat dissatisfied; (5) very dissatisfied; and (6) do not know.

2.1.3.4 Fuel Consumption

Concern for transportation energy consumption has become an important transportation policy issue since motor vehiclesare the single largest consumers of petroleum in the world (Meyer and Miller 2001). Methods in measuring fuel consumption are not the same as measuring air quality or noise quality. Meyer and Miller (2001) stated that the most common method to measure is by measuring the change number of vehicle miles associated with a particular freeway and multiply by a fuel consumption factor that reflects the average amount of fuel consumed per vehicle mile by vehicle type and model year.

The following steps are one of examples that Meyer and Miller gave in measuring the fuel consumption in Freeway:

- Step 1 : Categorize vehicles into some categories i.e. light-duty gasoline automobiles, light-duty gasoline trucks, medium-duty gasoline trucks, heavy-duty gasoline trucks, light-duty diesel automobiles, light-duty diesel trucks, heavy-duty diesel trucks, standard buses, articulated buses, and motorcycles.
- Step 2: Measure the percent total vehicle miles travelled for each vehicle type.
- Step 3: Multiply the percentVehicle Miles of Travel (VMT) by total VMT to calculate the daily VMT for each vehicle type.
- Step 4:Divide daily VMT by average fuel consumption in miles per gallon for each vehicle to determine the daily fuel consumption in gallons for each vehicle type.

- Step 5:Multiply daily fuel consumption by a constant BTUs per gallon of gas or diesel to give the daily vehicle energy consumption for each vehicle type.

2.2 Measurement Tools

Real-time traffic data collection is needed in freeway performance to get the actual condition of freeway, since the lack of data is often quoted as the major obstacle in managing the transportation systems, including the performance measurement, real-time operations and future demand forecast. In regards to collecting accurate data of freeway condition, the most popular method is by using Intelligent Transport System (ITS).

As can be noted in Smadi, Baker and Birst (2006, 642), there are two types of data collection that can be done: Permanent (continuous) or Temporary. Permanent counting stations record the freeway traffic performance and management continuously, this type includes the loop detector (single or double loop detector) and surveillance camera. Whilst the temporary collection is conducted to support only special studies, varied from traffic signal to parking lot operations which is most likely not used in freeways; video based and radar based systems that are proposed by Smadi, Bake and Birst (2006) in their paper. This thesis will focus on permanent data collection rather than temporary data collection.

Tools that are used for performance measurement are evolving as the development of technologies increases. For instance, the development of probe vehicle is originated in early 1970's in the course of a pilot with the Japanese Comprehensive Automobile Traffic Control System (CACS) which was sponsored by the government that aimed to develop the route guidance and traffic information system (Linnartz 2009). Even though probe vehicleswere developed in early 1970's, probe vehiclesare still used today. The reason is, probe vehiclesgive a real-time situation of traffic conditions, and proved to give more accurate data traffic condition compared to induction loop parameters (Lee and Rakotonirainyn.d.).

Technologies are still developing, the use of video surveillance for measuring freeway performance are also now used in measuring the freeway performance. Video surveillance is also applied for Traffic Incident Management that is also applied in Brisbane. Moreover, it is progressively being installed across the major traffic routes, with widespread coverage of the inner city area (Charlles et.al. 2003).

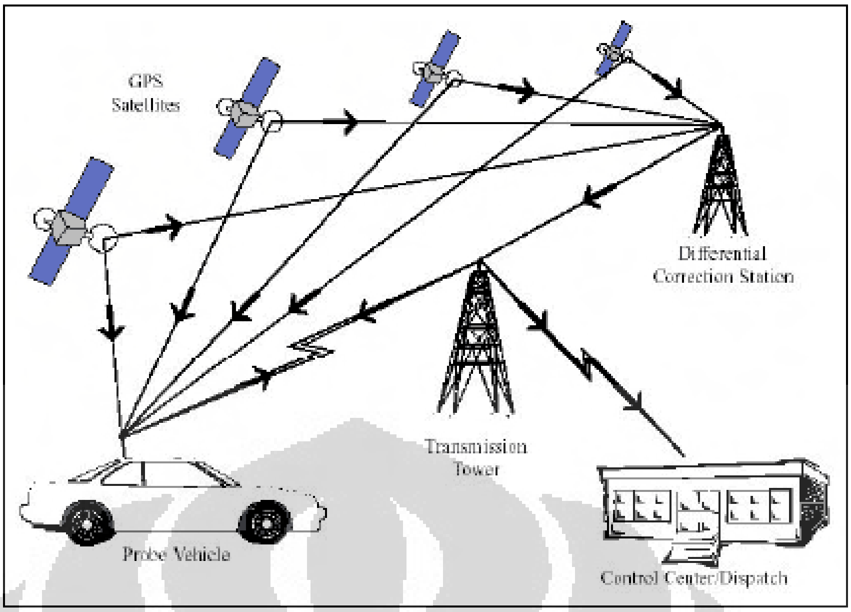
Other forms of tools also used in measuring freeway systems performance is inductive loops, either using single loops or double loops systems. The development of Freeway Performance Measurement (PeMS) in California is one of the example of inductive loops are utilized and developed in their transportation systems. A lot of research has been done in this area, to reach the maximum capability of tools in combination with other networking systems and by reducing the errors and issues regarding inductive loops application.

2.2.1 Probe Vehicle

Research and development about use of probe vehicles either for freeway performance measurement or incident management still occur in this present day, even though the early touch of probe vehicle use was developed for about 40 years ago. This proves that the probe vehicle is still needed in giving information for real-time operation monitoring, incident detection and route guidance. Using the development of wireless communication technology, probe vehicles can be classified as “mobile detectors”, they are considered as a valuable source of real-time traffic data (Chen and Chien 2001). There are some instruments that are used in probe vehicle. Most common instruments are:

- Global Positioning Systems (GPS)

  Probe vehicles are provided with GPS receivers to pick up signals from satellites. The positional information is transmitted to a Control centre to display the real-time position of probe vehicle and be prepared for analysis. Figure 7 overleaf shows the illustration of how the mechanism of probe vehicle using GPS systems works.



Source: Travel Time Data Collection Handbook / Detector Technology Evaluation (2003)

Figure 7Typical Configuration for Satellite-based Probe Vehicle System

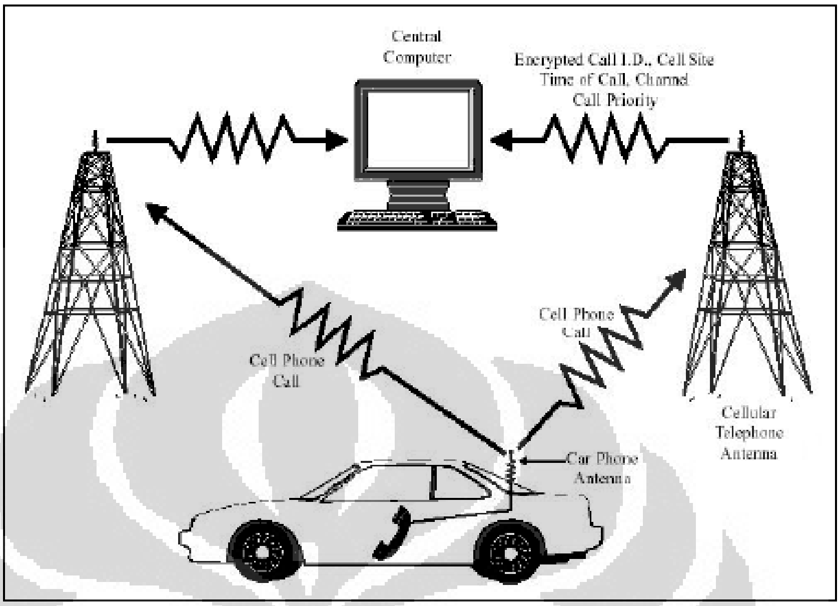
- Cellular Phone

  The mechanism of cellular reporting required volunteer drivers to call a central facility to report special identification, location and time at special point. Moreover, the travel time and speed can also be determined by calculating the time between successive telephone calls. Telephone calls can be located by using cellular geolocating, which will collect traffic information using existing vehicle locating devices, cellular telephone network and a central control facility. This system will automatically detect cellular telephone calls and the location of probe vehicle within seconds (Martin, Feng and Wang 2003).

  On the other hand, Wright, Carl, Luk (2006) technical difficulties were foundwhen using cellular phone as probe vehicles, these include:

  - Determining which phones are actually in motor vehicles (as opposed to those in the hands of people walking down the street or in rail cars on tracks beside freeways); and
  - Which roads a given phone happens to be travelling on (is it on the freeway or the frontage road?)

Figure 8 below shows the illustration of how the mechanism of probe vehicle using Cellular phones work.



Source: Travel Time Data Collection Handbook Detector Technology Evaluation (2003)

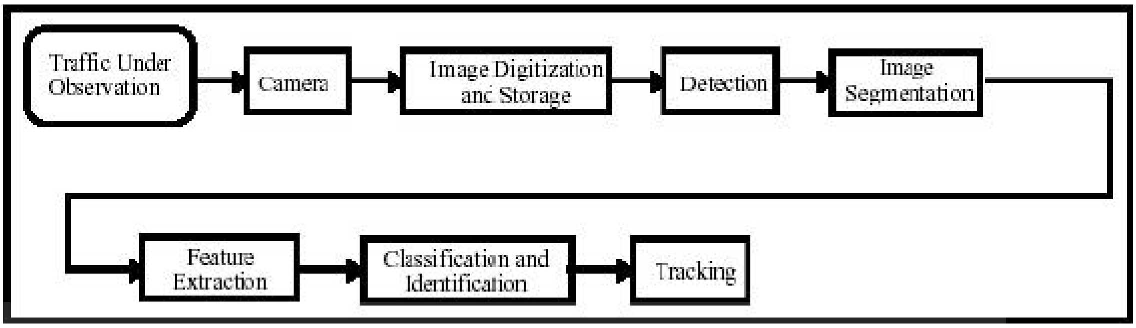
Figure 8Cellular Geolocation Communications

2.2.2 Video Image Processing (VIP)

VIP began to be introduced in U.S., Japan, U.K., Germany, Sweden, and France in the mid 1970s and 1980s. VIP systems consist of several video cameras, equipment for imaginary processing, and software for interpreting images and outputting data. VIP detectors are capable of monitoring multiple lanes and zones, wide-area detection, many data types, and flexibility. Other benefits of VIP detectors are lower cost, and improved application experience (Martin, Feng and Wang 2003).

One data that is measured by VIP is vehicle classification. The vehicle is classified by length and measures the volume, occupancy, presence, and speed for each vehicle class. Moreover, other data such as density, queue length, travel time, headway, and turning movements can be measured too (Martin, Feng and Wang 2003). Video surveillance can also be used to double check the incident information from the cellular phone vehicle probe.

Figure 9 below shows the image processing of VIP systems.

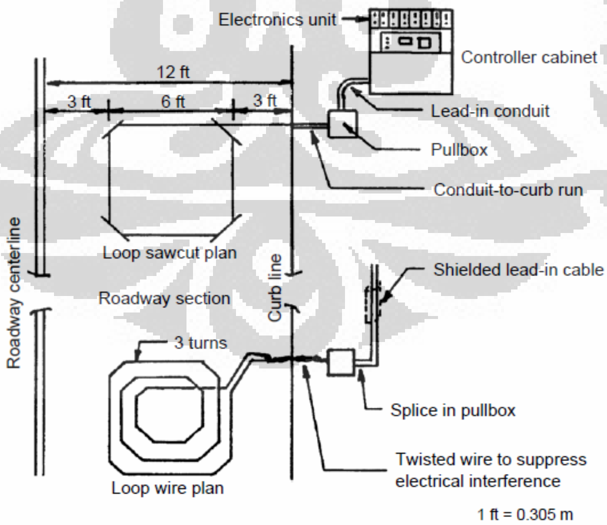


Source: Sensor Technologies and Data Requirements for ITS / Detector Technology Evaluation (2003)

Figure 9Conceptual Image Processing for Vehicle Detection, Classification, and Tracking

2.2.3 Inductive Loop

Inductive loops are categorized in Intelligent Transport Systems as intrusive detector that is the opposite of Probe vehicle and Video Image Processing. It is also the most common sensor used in traffic management (Mimbela and Klein 2007). Typically, inductive loops consist of a detector oscillator that acts as the detector energy source, a lead-in cable, and the insulated loop in a shallow slot of the pavement as shown in Figure 10 below.



Source: Detector Technology Evaluation a Summary of Vehicle Detection and Surveillance Technologies used in Intelligent Transportation Systems (2003)

Figure 10Principal components of an inductive loop detector (Mimbela and Klein 2007)

As can be noted from Martin, Feng and Wang research (2003), there are three types of loop installations: Trenched –in, preformed, and saw-cut. Preformed is not embedded in the pavement, but it has its own protector which is PVC pipe to hold their shape from pressure induced by vehicles. In addition, this preformed type is usually used on bridge decks. On the other hand, saw-cut and trenched-in loop types are different from preformed because they are installed embedded in pavement. Trench-in loop is installed below the pavement and saw-cut loop shape is installed by cutting the pavement in the shape of loop then laying the loop wire in the slot, filling the slot and then protecting the wire.

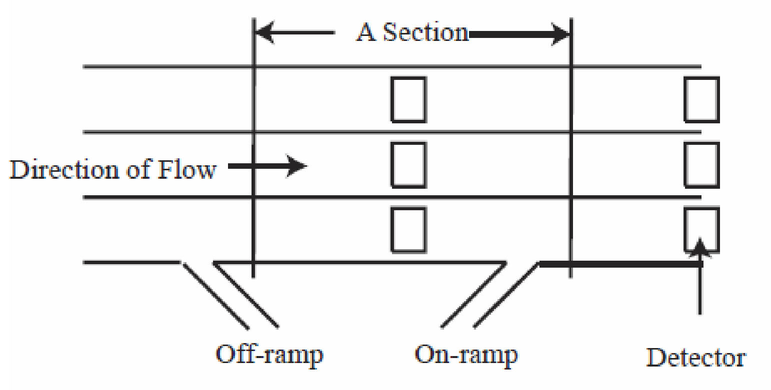
Inductive loops are typically used to measure the volume, occupancy, and speed. In order to give more information about loop detector practice, one example that is advanced in Freeway systems performance is taken: PeMS (California's intelligent transportation systems in freeway performance measurement). In California, PeMS placed inductive loops within spacing of one-third to one-half mile apart. Two numbers are reported from inductive loops every 30 s (e.g. flow and occupancy). In definition, the flow is number of vehicles that crossed the loops within 30s interval, flow is also usually referred to as count. Number of flow will be reported every hour in form of vehicle per hour (VPH). In addition, occupancy can be defined as fraction of the previous 30s that a vehicle was present over detector.

The occupancy equation:

$$Occupancy = \frac{Flow \times VehicleLength}{Speed}$$

Equation 3 Occupancy Equation

showed the relationship among occupancy, flow, vehicle length, and speed. In PeMS, terms of vehicle length is expressed in miles and speed is in miles per hour (mph). The congestion will occur when the occupancy value exceeds critical value. Terms of "a section" can be related to a set of detectors (one per lane) and may contain one off-ramp or on-ramp, as shown in Figure 11.



Source: Causes and Cures of Highway Congestion (2004)

Figure 11A section is a portion of highway at a detector location

2.2.4 Discussion on Measurement Tools Issue

Loop Detector

Even though loop detectors are widely used to measure the freeway performance, the use of loops detectors has some limitations that have been faced by engineers and planners. One of the limitations that is mentioned by Golob, Recker and Palvis (2007) is the loop detector data at specific time and place cannot be converted to speed, because it is not possible to know the effective vehicle length at such a detailed level (mix of short and long vehicle at a specific place for a period of time). Moreover, loop detectors also have a limitation in measuring congestion level. Vairaya (2002) argued that there are two factors that affect congestion and cannot be measured by loop detectors (e.g. occurrence of incidents and trip data). Another issue that is stated by Vairaya (2002) is that the loop detectors were placed one-half mile apart (in California) which is not possible for analyst to use the measurement to detect incidents quickly.

Moreover, the “health detector” of loops detector should be done regularly, in order to ensure the data quality that is produced is not contaminated with errors and bulks. Vairaya (2004) mentioned that there are two major types of contamination: missing data samples, and erroneous data samples. Facts that are shown by Vairaya (2004) prove that there are almost 40 percent of samples are missing or unreliable because of malfunctioning detectors.

The problems that can be found in loop detector are stated by Martin, Feng and Wang (2003). They argued that loop detectors have a relatively high failure rate. Specialized loop testers are often used to check the quality of data. Detection errors can be reduced and removed by using advanced methods of algorithms. It can be noted that the bad detectors can be detected by developing a method which is based on volume and occupancy measurement. Another method that has been developed, utilizes theory that time each detector is occupied by a vehicle and should be virtually identical at free flow velocities, regardless the vehicle length. After applying these methods the data quality is improved and makes inductive loop one of the most accurate count and presence detectors (Martin, Feng and Wang 2003). More detail about how to answer the issues on tools will not be discussed in this report.

Video Image Processing (VIP)

Since the loops detectors cannot detect the incident quickly, incident detection can be helped by using video cameras to improve incident detection. Video streams are typically checked manually which will limit the number of cameras that will be deployed. Therefore, video coverage is limited. (Vairaya 2002). Another limitation is faced due to the fact that, to expand the use of video camerasa relatively high-bandwidth communication link to transport the video data is required.

Limitations in using Video Image Processing tools are stated in Martin, Feng and Wang (2003) analysis, such as:

- Heavy rain that may reduce the visibility. The reflection on wet pavement also will affect VIP performance
- Wind swayed the pole that the detection pole was attached to, and the detection zones moved on and off the paint strip of the road
- The light condition is the one that will greatly affect VIP performance because detectors must have enough light either from sun or street light in order to detect image. The worse condition is performed by VIP when the transition from day to night.

CHAPTER 3

FREEWAY SYSTEMS PERFORMANCE ANALYSIS ON AUSTRALIAN NATIONAL PERFORMANCE INDICATOR

3.1 Introduction

Scope that will be discussed in this chapter is the Australian National Performance Indicators which are proposed by Austroads to analyse performance of a freeway. Those indicators are important and gave some equations and method of how freeways can be best measured. One of indicators that will be discussed more in this chapter is the Productivity Indicator.

According to Somers (2010), the productivity measurement is an equation which is based on the product of speed and flow. By comparing the product of actual speed and flow to the normalisation speed and flow, the productivity of a freeway can be obtained. As shown in the equation below:

$$Productivity = \frac{speed \times flow \times 100\%}{speed_{norm} \times flow_{norm}}$$ This equation applied for speed < normalisation speed

$= 100$ This Number applied for speed $\geq$ normalisation speed.

Normalisation speed and normalisation flow that were recommended by Austroads can be set at 80km/h and 2000pc/h/lane respectively.

There is not enough information on how the normalisation speed and flow are obtained, howevermodification on normalisation speed on managed freeways has been done by Somers (2010). The normalisation speed that he proposed was 65 km/h for managed freeway. However, the normalisation speed for unmanaged freeway was not discussed further in the literature review.

Investigation on the productivity equation revealed that the proposed equation is right, but there is not any limitation on which case the equation can be used. Somers (2010) has proposed other normalisation speedsthat is applicable for other cases which is for Managed Freeway, however the normalisation flow on the managed freeway was not mentioned by Somers (2010).

Furthermore, there is not any specific information about the Free Flow Speeds that are appropriate to the equation. For instance, a freeway with a speed limit 70 km/h will never ever get 100% productivity if using the same equation, normalisation speed and normalisation flow as proposed by Austroads to measure its productivity. Moreover, this equation also seems not applicable to Speed-Flow Rate curves for basic freeway segments on Highway Capacity Manual 2000. The free flow speeds that are stated on the Highway Capacity Manual 2000 is more than 80km/h which means that almost all of the highway sections that are discussed in Highway Capacity Manual will have a productivity value 100% in the NPI Productivity rule. Therefore, new normalisation values for particular cases are needed instead of using the same value for each freeway characteristic.

3.2 Aim

According to this Freeway systems performance related issue, the alternative value of normalisation speed and flow will be analysed for different speeds as stated on the Highway Capacity Manual 2000. Obtaining new adjusted normalisation values for speed and flow is the main objective of this chapter. Those new adjusted values should be able to indicate the productivity of a freeway according to the standard Speed-Flow Curve which is given in the HCM 2000.

3.3 Analysis

As mentioned before, analysis will use HCM Speed-Flow Curve for Basic Freeway Segment. The Speed-Flow Curves for Basic Freeway Segments can be seen on Figure 12 below.

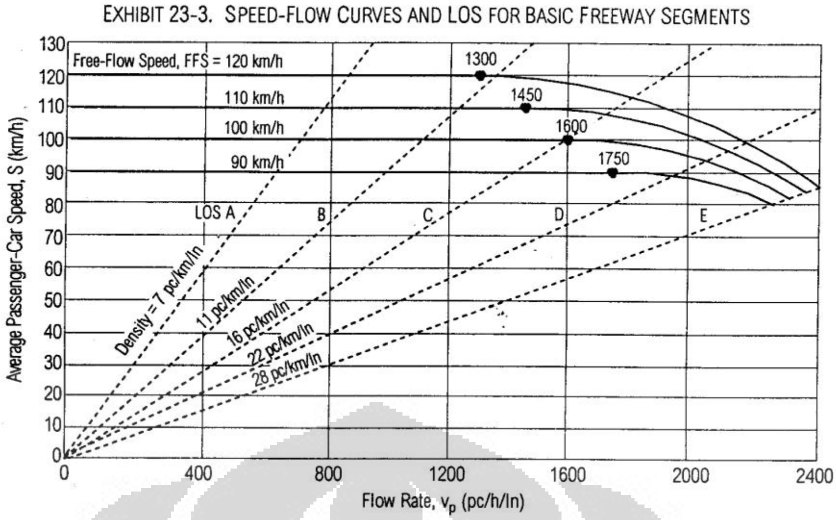


Figure 12Speed-Flow Curves for Basic Freeway Segments

3.3.1 Analysis Procedure

The procedure in order to get a result of new adjusted normalisation speed and flow is shown as follow:

- Determine the productivity (pc.km/hr/ln) of a basic freeway segments as stated on HCM 2000 by multiplying the speed (km/h) and the Flow Rate (pc/h/ln)
- Determine the adjusted normalisation speed and flow by choosing the speed and flow value from the maximum productivity
- Determine the productivity ratio by using the NPI normalisation speed and value

The NPI Normalisation Productivity can be seen from equation below:

$$NPI\text{Normalisation}Productivity = Speed_{norm} \times Flow_{norm}$$
$$= 80\, {}^{km}/_{h} \times 2000\, pc/h/ln$$
$$= 160{,}000\, pc.km/h/ln$$

$$ProductivityRatiobasedonNPIValues = \frac{ActualProductivity}{NPINormalisationProductivity}$$

- Determine the productivity ratio by using the new adjusted normalisation speed and value

$$ProductivityRatiobasedonAdjusttedValue = \frac{ActualProductivity}{AdjustedNormalisationProductivity}$$

- Compare the productivity ratio based on NPI values and productivity value based on adjusted value to get the differences and the idea

3.3.2 Analysis on 120 km/h Free Flow Speed

As mentioned in Section 3.3.1, the first step is determining productivity. The productivity that is obtained from the HCM 2000 Speed-Flow Curve can be seen in the following Figure:

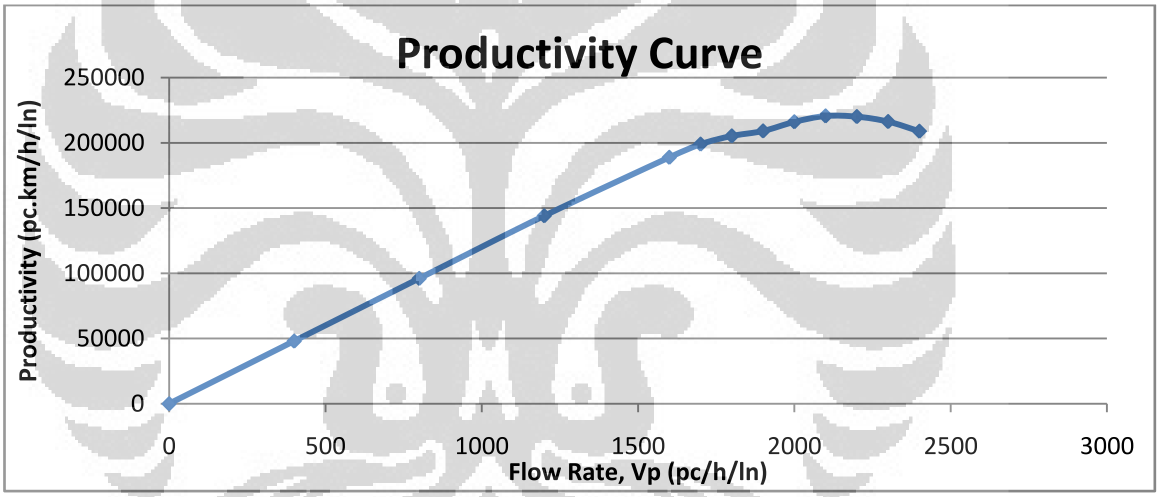


Figure 13 Productivity Curve for 120km/h

Based on Figure 13, the maximum productivity achieved is 220,500 pc.km/h/ln.Moreover, from this maximum productivity, the adjusted normalisation speed and flow values that can be obtained are 105 km/h and 2100 pc/h/ln respectively.

The comparison between two Productivity Ratios can be seen in Figure 14 overleaf.

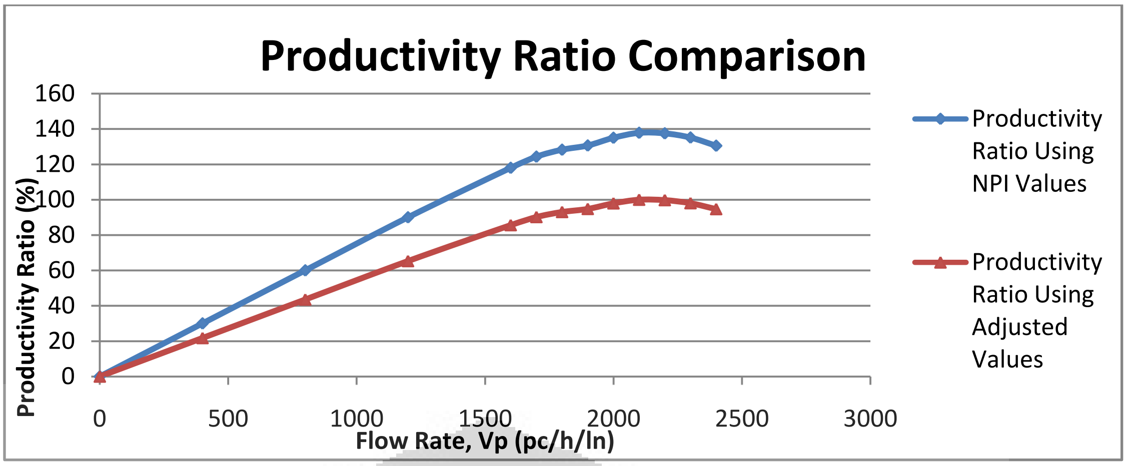


Figure 14Productivity Ratio Comparison on 120 km/h Free Flow Speed

3.3.3 Analysis on 110 km/h Free Flow Speed

The productivity that is obtained from the HCM 2000 Speed-Flow Curve can be seen in the following figure:

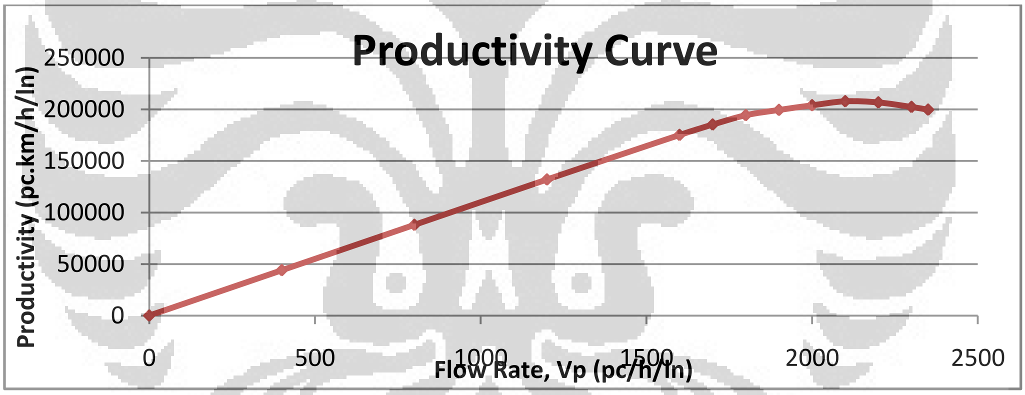


Figure 15 Productivity Curve for 110km/h

Based on Figure 15, the maximum productivity achieved is 207,900 pc.km/h/ln. Moreover, from this maximum productivity, the adjusted normalisation speed and flow values that can be obtained are 99 km/h and 2100 pc/h/ln respectively.

The comparison between two Productivity Ratios can be seen in Figure 16 overleaf.

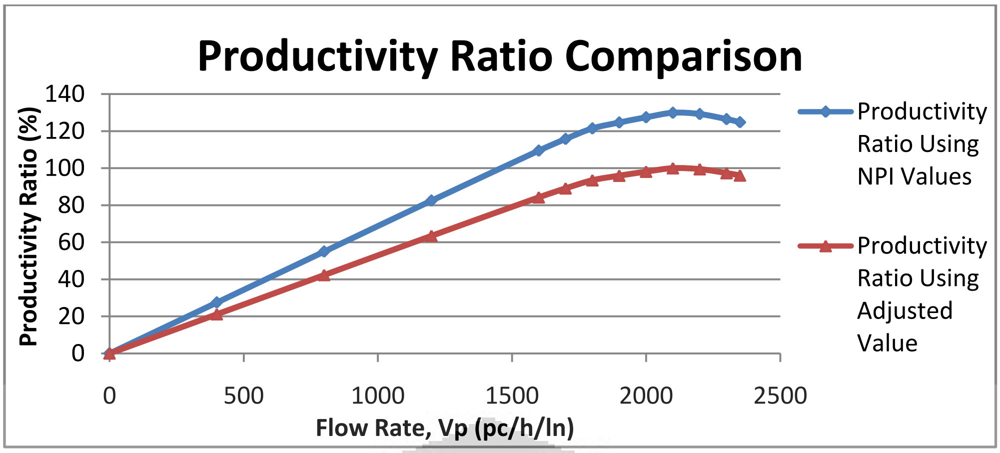


Figure 16 Productivity Ratio Comparison on 110 km/h Free Flow Speed

3.3.4 Analysis on 100 km/h Free Flow Speed

The first step is determining productivity. The productivity that is obtained from the HCM 2000 Speed-Flow Curve can be seen in the following figure:

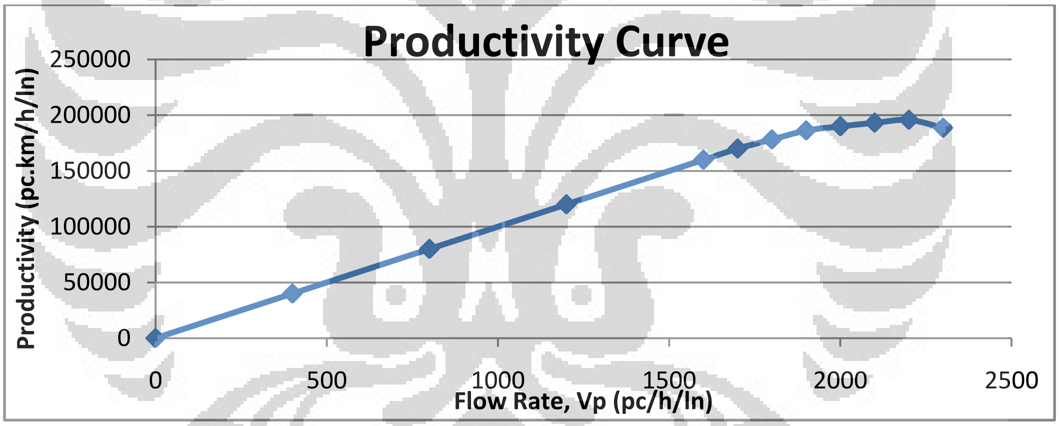


Figure 17 Productivity Curve for 100km/h

Based on Figure 17, the maximum productivity achieved is 195,800 pc.km/h/ln. Moreover, from this maximum productivity, the adjusted normalisation speed and flow values that can be obtained are 89 km/h and 2200 pc/h/ln respectively.

The comparison between two Productivity Ratios can be seen in Figure 18 overleaf.

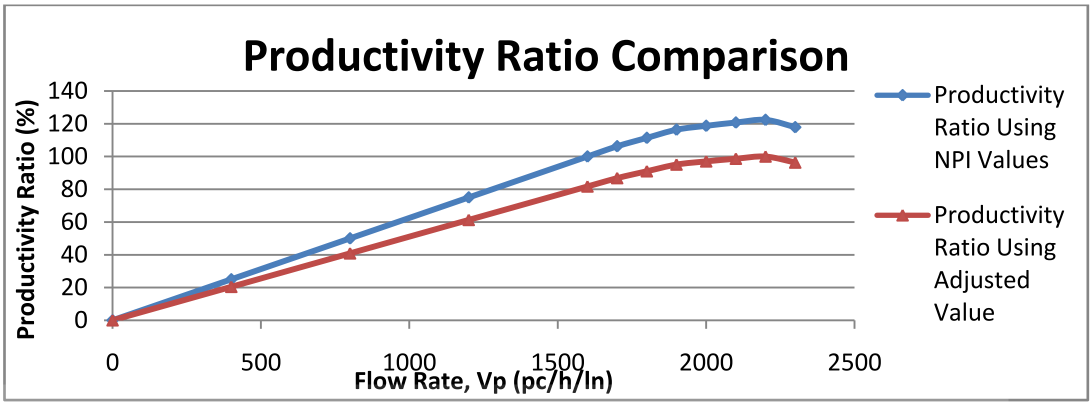


Figure 18 Productivity Ratio Comparison on 100 km/h Free Flow Speed

3.3.5 Analysis on 90 km/h Free Flow Speed

The first step is determining productivity. The productivity that is obtained from the HCM 2000 Speed-Flow Curve can be seen in the following figure:

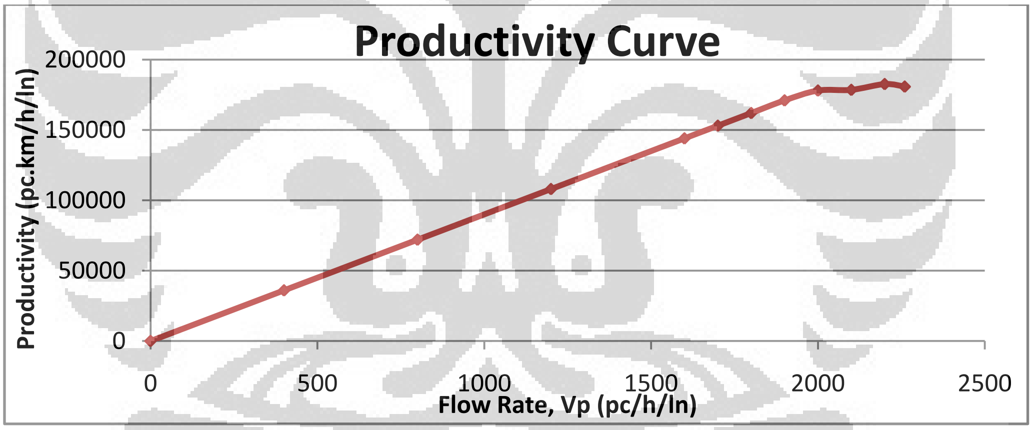


Figure 19 Productivity Curve for 90km/h

Based on Figure 19, the maximum productivity achieved is 182,600 pc.km/h/ln. Moreover, from this maximum productivity, the adjusted normalisation speed and flow values that can be obtained are 83 km/h and 2200 pc/h/ln respectively.

The comparison between two Productivity Ratios can be seen in Figure 20 overleaf.

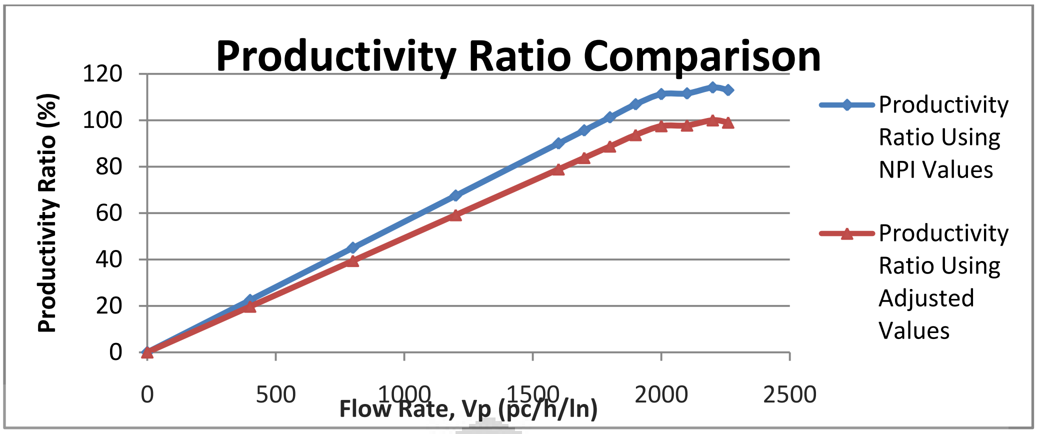


Figure 20 Productivity Ratio Comparison on 90 km/h Free Flow Speed

3.4 Discussion on Results

Based on analyses in the previous sections, it can be seen that all of the productivity ratios that are based on NPI normalisation values had ratio more than 100%. Those high productivity numbers were caused by two main reasons:

- The normalisation speed, 80km/h, is much smaller than the Free Flow Speeds which varied from 90km/h to 120 km/h
- The flow rates were higher than the normalisation flow rates, actual flow rates vary from 0 pc/h/lnto around 2400 pc/h/ln and normalisation flow rate is only 2000 pc/h/ln.This flow rate also gave another additional contribution to increase the productivity ratio

On the other hand, NPI tried to solve this issue by giving another rule which stated that if the speed is more than normalisation speed, 80km/h, then the productivity Ratio is directly converted to 100%. This correction method, which was proposed by Austroads, seems strange, because when this method was applied to the Speed-Flow Curve for Basic Freeway Segments which have Free Flow Speeds more than 80km/h, the productivity ratio increased from zero up to a certain point and then the graph plateaus at 100% without any fluctuation, even though the speed was decreasing when the flow rate was increasing. Figure 21 below shows one of the examples of productivity ratio on 120 km/h Free Flow Speed if the NPI correction method applied. Similar curve will also be obtained on 110km/h, 100 km/h, and 90 km/h Free Flow Speeds.

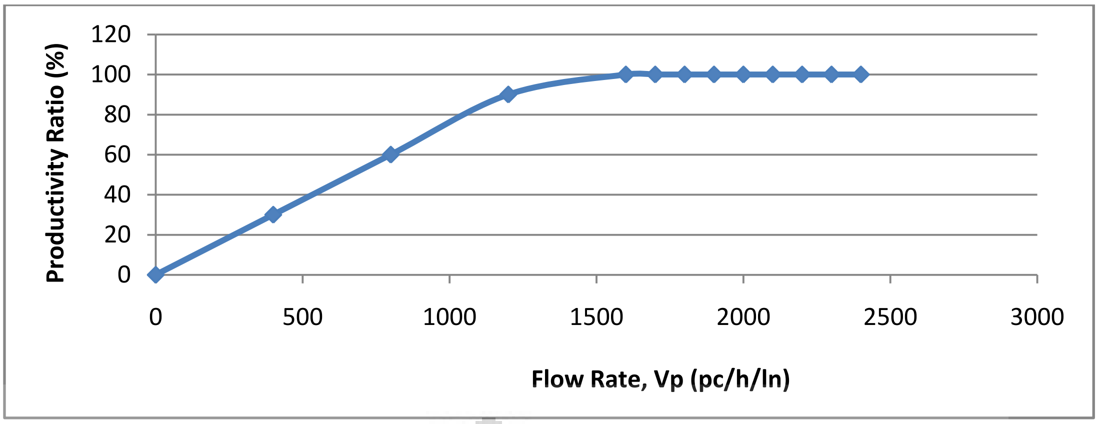


Figure 21 Corrected NPI Productivity Ratio on 120km/h Free Flow Speed

The graph in Figure 21 does not reflect the performance of a free way well, nor the productivity. For instance, it can be seen in Appendix A-Table1, the actual productivity of a freeway is decreasing after reaching a flow rate of 2100 pc/h/ln, which means that the productivity is not the same as the maximum productivity or on the other hand it is not 100%, but the Corrected NPI productivity always shows the freeway reaching maximum productivity.

Another type of correction should be used in order to get the actual productivity ratio of a basic freeway segment. A new adjusted normalisation is one of the other correction methods that can be used. In this method, normalisation speed and flow rate values should be chosen for each different free flow speed. In order to get a more general value for each Free Flow Speed, the Highway Capacity Manual 2000 is used as the standard curves.

In Figure 14, Figure 16, Figure 18, and Figure 20, the comparison between NPI productivity Ratio and Adjusted Productivity ratio can be seen. The adjusted normalisation value is more rational as it can be seen in those figures. The productivity decreased after the optimum productivity (100% productivity) due to the decreasing speed. Moreover, adjustable normalisation values also reflect the actual condition and the productivity of a freeway rather than the previous method (NPI Method) that gave greater than 100% productivity or corrected to flat 100% productivity. Furthermore, the adjusted normalisation values can also be referred to as optimum speed and optimum flow rate.

CHAPTER 4
RESULTS, DISCUSSIONS, AND SUMMARY

It has been shown in the previous analysis that the Freeway productivity measurement using NPI productivity equation does not have clear boundary and limitations on when the equation can be used, the NPI productivity equation also seemed to give an inaccurate reflection of the performance and productivity of a highway if the equation is substituted by values from HCM 2000 Speed-Flow Curves for Basic Freeway segments.

Based on the Analysis in Section 3, the result of adjusted normalisation speed and flow rate or the optimum speed and flow rate can be summarized into the following table:

Free Flow Speed (km/h)	Optimum Speed (km/h)	Optimum Flow Rate (pc/h/ln)	Optimum Productivity (pc.km/h/ln)
120	105	2,100	220,500
110	99	2,100	207,900
100	89	2,200	195,800
90	83	2,200	182,600

Table 6The Optimum Speed, Flow Rate, and Productivity

Another suggestion on measuring freeway systems performance, especially the productivity of the freeway is by getting the optimum free flow speed and optimum flow rate from the HCM 2000 Speed-Flow Curves for Basic Freeway segments curve that is shown in Table 6 above.

The distinction between the suggested method and the NPI method are:

- The normalisation speed and flow rate in NPI method is substituted respectively by Optimum Speed (Adjusted Normalisation Speed) and Optimum Flow Rate (Adjusted Normalisation Flow Rate)
- The correction method is still applicable, but with some modification, such as:

  If the productivity of a freeway is greater than 100% then it is directly converted to 100%

  - The corrected value will not be easily found in the calculation, because the new normalisation speed and flow rate is now reasonable for each particular FFS of a freeway.
  - The correction might happen if the recorded or actual Speed-Flow Curve for a Basic Freeway Segments is not exactly the same as the Speed-Flow Curve for a Basic Freeway Segments on HCM 2000

CHAPTER 5
FURTHER THEORY DEVELOPMENT

As can be seen in the previous sections, the developed theory is only based on a comparison between NPI productivity measurement and the Highway Capacity Manual 2000. Further research and development is needed in order to improve and give more detail of boundary conditionswhich requires more specific cases to measure the freeway performance, especially the freeway productivity. The developed theory should be investigated by measuring the real data of a basic freeway segment by using the developed theory.

It is proposed that the investigation of the number of lanes alsoaffect the freeway performance, this should also be undertaken. Study of the relationship between freeway performance and the number of lanes could be done by analysing the actual recorded data of a freeway which have different numbers of lanes;the theory developed from this investigation could then be used as more specific theory supporting the existing one.

It has been mentioned earlier that the analysis only used the HCM 2000 which has Free Flow Speeds (FFS) more than 80 km/h. More detail research could also be done by investigating the freeway performance wherethe speed limit is less than 80 km/h which may be possible because the speed limit of a particular freeway section is less than 80 km/h. However, the HCM 2000 cannot be used as the comparison because the stated FFS are more than 80 km/h. Therefore, the actual recorded data of a freeway section which has FFS less than 80 km/h is needed for this analysis.

CHAPTER 6
CONCLUSIONS

A measurement on freeway systems performance is important;it can be classified as the first step to reducingcongestion which is one of the major traffic issues. Since the freeway systems performance covers all measurements from mobility, safety to the environmental performance of a freeway. The mobility performance measurement is one of the best aspects that should be measured to give a picture of the current condition of a freeway, whetherit reaches the maximum productivity or not. Further improvement or action can be taken by the decision maker in order to maintain the freeway productivity.

As the technology is rapidly developing, the devices that are used in measuring the freeway performance especially mobility performance are also developed. The use of technology in measuring freeway performance can be seen in some devices that are commonly used in mobility performance, such as: Probe Vehicles, Video Image Processing and Inductive loops.

The analysis of the performance then can be done after the data is collected. There are some aspects and methods that can be done to measure the freeway performance. One of the ways that is suggested by Austroads is by considering the Australian National Performance Indicators which include Traveller efficiency, Traveller Efficiency, Traveller Efficiency, Reliability, and Productivity. The productivity measurement is a function of speed and flow rate, which can be obtained by the devices such as Inductive Loop.

According to the literature analysis, the productivity measurement that was proposed byAustroads did not mention the boundary or the limitation of the equation clearly. The normalisation speed and flow that has been given is not always applicable to all types of freeways.

An evaluation of the productivity measurement has been done by verifying the equation with the Speed-Flow Curves of basic freeway segments from Highway Capacity Manual 2000. Based on the study that has been discussed in Section 3, the productivity equation that was developed by Austroadsneeds to be modified to give a better image of the actual freeway productivity for each free flow speed as shown in the HCM 2000.

Based on the analyses, new recommended valuesof normalisation speed and flow are:

- FFS = 120 km/h. Normalisation (optimum) speed is 105 km/h and normalisation (optimum) flow rate is 2100 pc/h/ln
- FFS = 110 km/h. Normalisation (optimum) speed is 99 km/h and normalisation (optimum) flow rate is 2100 pc/h/ln
- FFS = 100 km/h. Normalisation (optimum) speed is 89 km/h and normalisation (optimum) flow rate is 2200 pc/h/ln
- FFS = 90 km/h. Normalisation (optimum) speed is 83 km/h and normalisation (optimum) flow rate is 2200 pc/h/ln

By using above values, the productivity of a freeway that can be obtained is more reasonable and more specific for each different speed. In order to keep it still reasonable, therefore, another rule should be added which is **If the productivity of a freeway is greater than 100% then it is directly converted to 100%.**

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Appendices

Appendix A – 120 km/h Free Flow Speed Data

speed (km/h)	Flow Rate (pc/h/ln)	Productivity (pc.km/hr/ln)
120	0	0
120	400	48000
120	800	96000
120	1200	144000
118	1600	188800
117	1700	198900
114	1800	205200
110	1900	209000
108	2000	216000
105	2100	220500
100	2200	220000
94	2300	216200
87	2400	208800

Table 1 Productivity Value of 120 km/h of Free Flow Speed

Flow Rate (pc/h/ln)	Productivity Ratio Using NPI Values (%)	Productivity Ratio Using Adjusted Value (%)
0	0	0
400	30	21.77
800	60	43.54
1200	90	65.31
1600	118	85.62
1700	124.31	90.20
1800	128.25	93.06
1900	130.63	94.78
2000	135	97.96
2100	137.81	100
2200	137.5	99.77
2300	135.13	98.05
2400	130.5	94.69

Table 2 Productivity Ratio Comparison on 120km/h Free Flow Speed Flow Speed

Appendix B – 110 km/h Free Flow Speed Data

speed (km/h)	Flow Rate (pc/h/ln)	Productivity (pc.km/hr/ln)
110	0	0
110	400	44000
110	800	88000
110	1200	132000
109.5	1600	175200
109	1700	185300
108	1800	194400
105	1900	199500
102	2000	204000
99	2100	207900
94	2200	206800
88	2300	202400
85	2400	199750

Table 1 Productivity Value of 110 km/h of Free Flow Speed

Flow Rate (pc/h/ln)	Productivity Ratio Using NPI Values (%)	Productivity Ratio Using Adjusted Value (%)
0	0	0
400	27.5	21.16
800	55	42.33
1200	82.5	63.49
1600	109.5	84.27
1700	115.81	89.13
1800	121.5	93.51
1900	124.69	95.96
2000	127.5	98.12
2100	129.94	100
2200	129.25	99.47
2300	126.5	97.35
2400	124.84	96.08

Table 2 Productivity Ratio Comparison on 110km/h Free Flow Speed Flow Speed

Appendix C – 100 km/h Free Flow Speed Data

speed (km/h)	Flow Rate (pc/h/ln)	Productivity (pc.km/hr/ln)
100	0	0
100	400	40000
100	800	80000
100	1200	120000
100	1600	160000
100	1700	170000
99	1800	178200
98	1900	186200
95	2000	190000
92	2100	193200
89	2200	195800
82	2300	188600

Table 1 Productivity Value of 100 km/h of Free Flow Speed

Flow Rate (pc/h/ln)	Productivity Ratio Using NPI Values (%)	Productivity Ratio Using Adjusted Value (%)
0	0	0
400	25	20.43
800	50	40.86
1200	75	61.29
1600	100	81.72
1700	106.25	86.82
1800	111.38	91.01
1900	116.38	95.1
2000	118.75	97.04
2100	120.75	98.67
2200	122.38	100
2300	117.88	96.32

Table 2 Productivity Ratio Comparison on 100km/h Free Flow Speed Flow Speed

speed (km/h)	Flow Rate (pc/h/ln)	Productivity (pc.km/hr/ln)
90	0	0
90	400	36000
90	800	72000
90	1200	108000
90	1600	144000
90	1700	153000
90	1800	162000
90	1900	171000
89	2000	178000
85	2100	178500
83	2200	182600
80	2300	180800

Table 1 Productivity Value of 90 km/h of Free Flow Speed

Flow Rate (pc/h/ln)	Productivity Ratio Using NPI Values (%)	Productivity Ratio Using Adjusted Value (%)
0	0	0
400	22.5	19.72
800	45	39.43
1200	67.5	59.15
1600	90	78.86
1700	95.63	83.8
1800	101.25	88.72
1900	106.88	93.65
2000	111.25	97.48
2100	111.56	97.75
2200	114.13	100
2300	113	99.01

Table 2 Productivity Ratio Comparison on 90km/h Free Flow Speed Flow Speed