A decision support system for the choice of medium-capacity transit system

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2010

Tsai, Y. L. (2010). A decision support system for the choice of medium-capacity transit system. Master's thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/40920>

<https://doi.org/10.32657/10356/40920>

**NANYANG
TECHNOLOGICAL
UNIVERSITY**

**A DECISION SUPPORT SYSTEM FOR THE CHOICE
OF MEDIUM-CAPACITY TRANSIT SYSTEM**

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SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

2010

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**A thesis submitted to the Nanyang Technological University
in fulfillment of the requirement for the degree of
Master of Engineering**

2010

ACKNOWLEDGEMENTS

It is a pleasure to thank the many people who made this thesis possible.

Foremost, I would like to express my sincere gratitude to my supervisor, Prof. Henry Fan, for his valuable guidance and support of my study and research. With his enthusiasm, inspiration, and patience, he provided me encouragement, sound advice, and good teaching, so the thesis can be completed today. He also assisted me throughout my life at Nanyang Technological University. I could not have imagined having a better supervisor for my Master degree study.

Besides, I would like to thank the co-supervisors of my research: Prof. Lum Kit Meng and Prof. Hsu Tien-Pen, for their encouragement and assistance. My sincere thanks also go to the friendly staff members in CEE and Transportation Lab., particularly to Ms. Ng Soo Ching, Ms. Ng-Ho Choo Hiang, and Mr. Liew Kai Liang, for all the supports and helps they provided.

I thank my labmates and friends in Singapore for providing a stimulating and fun environment in which to learn in Singapore. I am especially grateful to Ya-Ching, Jianwen, Feng Zi, Chien-Hong, Ke-Chieng, and Rachael, for all the support, entertainment, and caring they provided. Also I thank my best friends, Wei-Yin, Yi-Ting, Yi-Fan, and Jun-Ming, for their encouragement and emotional support. I would also like to express my heartfelt gratitude to my boyfriend, Sheng-Wen, for his support, patience, and helping me get through the difficult times in these years.

Last, and most importantly, I wish to thank my parents. They bore me, raised me, supported me, taught me, and loved me. To them I dedicate this thesis.

SUMMARY

The rapid growth in many urban areas has resulted in traffic congestion, social inequity, and environmental problems. To control these problems, many cities have turned to urban transit systems to serve travel demand. The mass rapid rail transit (MRT) system has been implemented in many metropolitan areas. However, many cities do not have either the financial resources to afford a MRT system or the passenger demand to justify it. To improve public transport services, what is needed for such cities is an appropriate transit system which has higher capacity than a regular bus (RB) system and cheaper than the MRT. There are several medium-capacity transit systems that can meet this requirement. Such systems include Bus Rapid Transit (BRT), Light Rapid Transit (LRT), Guided Bus, Automated Guideway Transit (AGT) and Automated Light Rapid Transit (ALRT). Clearly, in the selection of an appropriate medium-capacity transit system for a study area, the option of retaining the existing transit system (usually RB) should also be considered as an alternative.

In the past, studies that dealt with the evaluation of alternative transit systems have been largely based on either a single factor (often cost), or on a few factors but with the alternatives compared on each factor individually. To select a suitable public transit system, one has to simultaneously consider and compare several system attributes some of which are quantitative while others are qualitative. In this research, the evaluation shall include both performance and sustainability attributes. After examining a set of preliminary performance and sustainability factors, three attributes are selected for testing the technical feasibility of each transit system

alternatives and twelve attributes are used for comparing these alternative systems.

A methodology is developed in this study to integrate these decision factors (i.e., system attributes) in the selection of an appropriate medium-capacity transit system for a given area in a rational and organized manner. The method is an improved version of the MEQQD method and uses the Weighted Least-Squares Method in its evaluation of the alternatives. To facilitate the use of the developed methodology by transit planners, it is implemented in the form of an easy-to-use Decision Support System (DSS). Such systems are a specific class of computerized information system that supports specific fields to do organizational decision-making activities. The C# language is used for building a DSS interface. For users who do not have their own site-specific data, the DSS also includes some default values for the various attributes included in the evaluation of the alternative systems. With the use of the DSS developed in this study, the finance and index rankings of each alternative are provided so that the user can take his budget limit and the rankings into consideration, and select the best alternative system for his specific situation.

Finally, the extension line of the Damsui rapid transit system in Taipei is included as a case study to demonstrate the application of the DSS. The results from the DSS suggest that using *LRT* for the *Blue Ocean Line – Tai 2 Line* is the optimal combination of transit line and medium-capacity transit system for that study area.

Keywords: Medium-Capacity Transit System, Sustainability, MEQQD, DSS

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LIST OF SYMBOLS

Symbol	Unit	Description
$\%A_{ipm'}$	%	Percentage of mode m' in period p w alternative i implementation
$\%B_{pm'}$	%	Percentage of mode m' in period p w/o alternative i implementation
$\alpha A_{ipm'}$	people/veh	Occupancies of mode m' n period p w alternative i implementation
$\alpha B_{pm'}$	people/veh	Occupancies of mode m' in period p w/o alternative i implementation
$a_{jj'}$	-	the difference in the measured levels of qualitative attributes between alternative j and alternative j'
$ACO_2A_{ipm'}$	ton/veh-km	CO ₂ emission per vehicle-km from mode m' in period p in its average speeds with alternative i implementation
$ACO_2B_{pm'}$	ton/veh-km	CO ₂ emission per vehicle-km from mode m' in period p in its average speeds w/o any alternative implementation
AD	\$/trip	Average trip distance for passenger transport
AH_i	min/TU	Average headway for alternative i
APA_i	g/TU-km	Air pollutant amount of alternative i per TU-km
$AAPA_{ipm'}$	g/veh-km	Air pollution per vehicle-kilometer by mode m' in its average speed in period p with alternative i implementation
$AAPB_{pm'}$	g/veh-km	Air pollution per vehicle-kilometer by mode m' in its average speed in period p w/o alternative implementation
ASA_{ipm}	km/hr	Average travel speed by mode m in period p with alternative i
ASB_{pm}	km/hr	Average travel speed by mode m in period p w/o alternative
ATA_{ii}	hr/pax	Average travel time of the passengers of alternative i
ATA_{ipm}	hr/person	Average travel time by mode m in period p with alternative i
ATB_{pm}	hr/person	Average travel time by mode m in period p w/o alternative
AW	\$/hr	Average wage

$b_{jj'}$	-	the standardization of the dominance level of qualitative attributes for alternative j compared to alternative j'
C	pax/hr	Maximum offered line capacity of a transit line
c	veh/hr	Line capacity in vehicles of a transit line
$c_{jj'}$	-	The difference in the measured levels of quantitative attributes between alternative j and alternative j'
C_v	pax/veh	Capacity of a vehicle
C_{TU}	pax/TU	TU capacity
CO_2A_i	ton/TU-km	CO_2 emission of the alternative i per TU-km
$CVOT_i$	\$/yr	Total congestion benefit for alternative i in a \$ unit
$d_{jj'}$	-	The standardization of the dominance level of quantitative attributes for alternative j compared to alternative j'
$DB_{pm'}$	km/yr	Total annual vehicle distances traveled by mode m' in period p w/o any alternative implementation
$DA_{ipm'}$	km/yr	Total annual vehicle distances traveled by mode m' in period p with alternative i implementation
e_{ij}	-	the value of attribute i for alternative j
$\bar{e}$	-	The standardized value of e_{ij}
$e_{i,best}$	-	Best values for attribute i among all alternatives
$e_{i,worst}$	-	Worst values for attribute i among all alternatives
e_{Mj}	-	Measure of new monetary attribute of alternative j
f_{max}	TU/hr	The maximum number of TUs passing a fixed point per hour
h	min/TU	Headway, time interval between two successive TUs
h_{min}	min/TU	Minimum headway
$h_{w min}$	min/TU	Way minimum headway (for line sections without stations)

$h_{s\ min}$	min/TU	Station minimum headway (time interval between successive TUs at stations)
L_i	km	Total length of the line/network for alternative i
m	-	{the set of modes, which includes passenger car, motorcycle, commercial car, and existing transit system}
m'	-	{the set of modeds, which includes passenger car, motorcycle, and existing transit system}
M	-	{the set of all attributes which are expressed in \$/year}
n	veh/TU	Number of vehicles per TU
nA_{ip}	veh/yr	Annual volume in period p with alternative i implementation
$nA_{ipm'}$	veh/yr	Annual volume by mode m' in period p with alternative i implementation
nB	veh/yr	Annual volume by passenger transport vehicles w/o alternative
nB_p	veh/yr	Annaul volume by passenger transport vehicles in period p w/o alternative
$nB_{pm'}$	veh/yr	Annual volume by mode m' in period p w/o alternative
NA_i	people/yr	Annual number of trips in people number with alternative i implementation
NA_{ii}	pax/yr	Annual number of trips in passenger number by using transit alternative i
$NA_{im'}$	people/yr	Annual number of trips in people number using mode m' with alternative i
NA_{ipm}	people/yr	Annual number of trips in people number using mode m in period p with alternative i
$NA_{ipm'}$	people/yr	Annual number of trips in people number using mode m' in period p with alternative i
NB	people/yr	Annual number of trips in people number w/o alternative i

$NB_{m'}$	people/yr	Annual number of trips in people number by mode m' w/o alternative i
NB_{pm}	people/yr	Annual number of trips in people number using mode m in period p w/o alternatives
$NB_{pm'}$	people/yr	Annual number of trips in people number using mode m' in period p w/o alternatives
p	-	{the set of periods which includes peak and off-peak periods}
P_{max}	pax/hr	One-way passenger demand among all sections of the line at the 30 th highest volume hour of the year
RAP_i	ton/yr	Air pollution reduction after the implementing alternative i ,
RCO_{2i}	ton/yr	The reduction in CO ₂ emission after the implementation of an alternative i
s_j	-	Appraisal scores of alternative j
$T_{walk\ i}$	min/pax	Average access/egress time of the passengers of alternative i
$T_{wait\ i}$	min/pax	Average waiting time of the passengers of alternative i
$T_{IVT\ i}$	min/pax	Average in-vehicle time of the passengers of alternative i
$TAPA_i$	g/yr	Total air pollutant amount with alternative i implementation
$TAPA_{ii}$	g/yr	Annual air pollutant amount for alternative system i
$TAPA_{im'}$	g/yr	Air pollutant amounts from mode m' with alternative i implementation
$TAPB$	g/yr	Annual total air pollution w/o implementing alternative i
$TAPB_{m'}$	g/yr	Annual air pollution by mode m' w/o implementing alternative i
TC_i	hr/yr	Total congestion benefits for alternative i in time unit
TCO_{2A_i}	ton/yr	Total CO ₂ emission with implementing alternative i .
$TCO_{2A_{ii}}$	ton/yr	Total annual CO ₂ emission of alternative system i
$TCO_{2A_{im'}}$	ton/yr	Total annual CO ₂ emission by mode m' with alternative i implementation
TCO_{2B}	ton/yr	Total CO ₂ emission w/o any alternative

$TCO_2B_{m'}$	ton/yr	Total annual CO ₂ emission from mode m' w/o alternative implementation
TOT_i	min/yr	Total operating time per year for alternative i
TTB	hr/yr	Total travel time in the area without any alternative
TTB_p	hr/yr	Total travel time in period p w/o any alternative
TTA_i	hr/yr	Total travel time in the area with alternative i implement
$TTA_{i_existed}$	hr/yr	Total travel time by existed modes (including all modes m) with alternative i
TTA_{ii}	hr/yr	Total travel time of passengers using alternative i
TTA_{ip}	hr/yr	Total travel time in period p with alternative i
VOT	\$/hr	Value of time, the ratio of the marginal utilities of time and money
VOT_p	\$/hr	Value of time in period p
V	-	Equivalent dollars of virtual money to \$1 of real money
W_i	-	The weight assigned to qualitative attribute <i>i</i> .
W_i^*	-	The weight assigned to quantitative attribute <i>i</i>

CHAPTER 1 INTRODUCTION

The rapid growth of many urban areas has resulted in excessive use of passenger vehicles to meet travel needs. This has caused problems such as traffic congestion, energy consumption, air pollution, social inequity, and so on. To control these problems, many cities have turned to the development of urban transit systems to serve the ever-increasing demand for travel.

1.1 Problem Identification

Many forms of urban transit systems, ranging from regular buses (RB) and tramways to Mass Rapid Transit (MRT) system, have been adopted around the world. Historically, RB is the most often used system because of its low cost and technology requirements, flexibility as well as easy implementation. However, it has drawbacks such as low capacity and speed, poor safety and comfort, as well as unsatisfactory service performance. Coupled with a rising awareness of the dangers of climate change, many cities are searching for an improved transit system to replace RB.

Over the years, new transit systems have been developed that offer better performance and appearance than RB. Among these, the mass rapid rail transit (MRT) system has been implemented in many metropolitan areas due to its high capacity and good performance. However, the high costs of providing a MRT system meant few cities have the financial resources to afford it. Furthermore, most cities do not have the passenger demand needed to justify such a high capacity MRT system. To improve public transportation services, what is needed for cities that do

not have the budget and/or passenger demand is an appropriate transit system which is more advanced than RB and cheaper than MRT.

There are several transit systems that can provide better performances (higher capacity and speed, better safety, and less environmental concerns) than RB, at costs that are substantially lower than those of MRT. Collectively, these systems are known as medium-capacity transit systems. They include bus rapid transit (BRT), light rail transit (LRT), guided bus (GB), light rail rapid transit (LRRT), and automated guided transit (AGT). According to some studies, medium-capacity transit systems such as LRRT and AGT can almost match the performance level of the MRT system.

Each of the medium-capacity transit systems has its own advantages and disadvantages. In addition, the situation, site characteristics and requirements vary from one city to another. Hence, different systems would suit cities with different characteristics and requirements, and it is not easy to choose an optimal system for a given city. Although several past studies compared the merits of some medium-capacity transit systems, the comparisons were often based on a single criterion such as cost. Using only one criterion to compare and select a transit system is not adequate. There are several other criteria, such as quality of life and environmental concerns that both users and non-users are concerned with.

A few recent studies did compare transit systems using a larger number of criteria. However, these studies only evaluated the alternative systems on a criterion-by-criterion basis, rather than integrating all criteria in their analysis. Such an evaluation usually does not result in a transit system that meets the requirements

of the city concerned. Urban planners and decision makers need a methodology which can simultaneously consider most if not all of their requirements and provide a holistic comparison of the alternative systems that would result in the most suitable transit system for their cities.

Therefore, it is desirable that an objective evaluation process is available for the selection of an appropriate medium-capacity transit system for a specific city. Such a tool would provide the decision makers with information to better understand which medium-capacity transit system is the most appropriate for their city.

1.2 Objectives and Scope

The objective of this research is to develop a methodology for comparing medium-capacity transit systems based on selected system attributes. This evaluation will include the integration of several criteria that are of relevance. Clearly, the reasons for eliminating RB (i.e., low capacity and speed, poor safety, and environmental problems) and the reason for not selecting MRT (i.e. high cost) are important factors to include in considering which alternative medium-capacity transit systems is the most appropriate.

In general, these factors may be classified into two groups: (a) ‘performance’ factors such as capacity and speed/travel time; and (b) ‘sustainability’ factors, which may be further divided into social-, environmental-, and economic-sustainability. Accordingly, the system attributes be divided into attributes associated with ‘performance’ and ‘sustainability’.

It is noted that, for some areas, retaining the existing transit system may provide

better performance and sustainability than constructing a new medium-capacity transit system. Therefore, the evaluation of alternative medium-capacity transit systems will also consider the existing transit system as an alternative (i.e., the so-called “Do-nothing” alternative) so that a comprehensive assessment can be undertaken.

In view of the fact that a regular bus system is the most often found transit system in many cities, it is used in this study to represent the existing transit system. In addition, even when a medium-capacity transit system is selected for an area, it cannot replace the regular bus services completely. Indeed, only a relatively few bus routes will be replaced in most cases. Therefore, the regular bus services referred to as the “do-nothing” alternative in this study covers only the existing bus routes that the alternative medium-capacity transit systems will replace when one is selected and implemented.

To facilitate the application of the developed methodology, an easy-to-use decision support system (DSS) will be implemented to assist planners and decision makers in the selection of the most suitable medium-capacity system for a given city. The DSS would provide options for the planners to use either site-specific data if these are available to them, or input data that are built into the system. The latter will come from data obtained from the literature or past studies in transit system planning.

To achieve the research objectives, the study will focus on the following tasks. The study approach is also illustrated in the flow chart shown in Figure 1.

1. A review of the literature covering the major published work in fields relevant

to this research. In particular, the state-of-the-art in multiple-attribute decision making, and methodologies for measuring system attributes and assigning weights to these attributes for evaluation.

2. Identification of alternative medium-capacity transit systems and their characteristics, as well as understanding the major considerations in the selection of system attributes (criteria) that are most relevant for evaluating transit systems.
3. Development of a methodology to integrate multiple selection criteria in the evaluation of medium-capacity transit systems based on relevant system attributes.
4. Collection of input data that will serve as default attribute values to be built into the DSS in the event site-specific data are not available.
5. Implementation of an easy-to-use decision support system. After the framework and details of the DSS have been established, an interface will be built to assist decision makers in applying this system to arrive at the most appropriate medium-capacity transit system that meets their specific requirements.
6. Conduct a case study to demonstrate the application of the developed DSS.

1.3 Design of the Study

Several assumptions are made in this study. These assumptions are introduced below:

1. The overall travel demand in the study area remains unchanged after the

- implementation of an alternative transit system. That is, the overall Origin Destination (O-D) trip table remains the same with or without an alternative transit system, what will change is the modal split. However, a user can input a revised trip table for a second round of analysis if it is believed that demand will change with the introduction of a new transit system.
2. If a trip involves more than one mode, only the main travel mode is considered because the other modes are just feeder services used to access the main mode and would not affect the evaluation of alternative transit systems.
 3. The line length of the ‘do-nothing’ alternative, which refers to the regular buses that will be replaced if an alternative transit system is built, is assumed to be the same as the line length of other transit systems.
 4. For passenger cars, motorcycles and regular buses which do not belong to the ‘do-nothing’ alternative, the average distance travelled per vehicle remains unchanged after the introduction of an alternative transit system.

1.4 Organization of this Report

The remainder of this thesis is organized into six chapters. Chapter 2 provides a review of relevant publication in the literature. Chapter 3 gives a description of the alternative medium capacity transit systems included in this study and the characteristics of each system. Chapter 4 defines the selected system attributes and discusses the study approach and methodology. Chapter 5 documents the development of the DSS. Chapter 6 presents an easy-to-use interface for the application of the DSS and uses the extension line of the Damsui rapid transit system in Taiwan as a demonstration of the DSS. Finally, the conclusions and recommendations for this study are discussed in Chapter 7.

Figure 1 Study Approach Flow Chart

CHAPTER 2 LITERATURE REVIEW

Previous research work done in relevant fields is reviewed in this chapter with special emphasis on the definition for medium-capacity transit systems, attributes for comparison, and methodologies for multiple attributes evaluation. This literature review starts with a short introduction on the classification of urban public transport, and defines the term ‘Medium-Capacity Transit Systems’. This is followed by a description of research about medium-capacity transit systems comparison. After that, the characteristics of selected attributes (indicators for comparison) are reviewed in more detail in section 2.3. The methods for assessing weight, Multi-Attributes Evaluation (MAE) methodologies, and a review of Decision Support System (DSS) are then discussed. Finally, the focus of this study as a result of this literature review is presented.

2.1 Classification of Urban Public Transport

Technically, urban public transportation includes both transit and paratransit categories, since both are available for public use. However, the term public transport is commonly identified with transit only, and paratransit is only included when mentioned specifically. Therefore, urban public transportation generally can be defined as transport systems with fixed routes and schedules, available for use by those who pay the established fare. The most common representatives are bus, light rail transit, and rapid transit or metro (Vuchic, 2007).

There are different ways of classifying transit modes in previous studies, and most of them use three classification categories. Some studies used a strict definition to

sort them into low-capacity modes (paratransit), medium-capacity modes (street transit), and high-performance modes (semirapid transit and rapid transit) (Vuchic, 1981); Chang used a generalized classification based on capacity (Chang, 1987; Chang and Wey, 1992). Still others categorize them into street transit modes, medium-capacity modes (semirapid transit), as well as high-performance modes (rapid transit) (Chan, 1994; Vuchic, 2007). The various classifications of transit modes used in past studies are summarized in Table 2.1:

Table 2.1 Classification of transit modes by previous studies

Study Year	Categories		
	Transit modes		
Vuchic (1981)	Low-capacity modes	Medium-capacity modes	High-capacity modes
	Paratransit (Taxis, D/R, Jitney)	Street transit (RB, TB, SCR and tramway)	Semirapid and rapid transit (Semirapid: SRB, LRT) (Rapid: LRRT, RTRT, RRT)
Chang (1987)	Low-capacity modes	Medium-capacity modes	High-capacity modes
	one-way capacity/hr: 5,000 below	one-way capacity/hr: 5,000-30,000	one-way capacity/hr: 25,000 up
Chang and Wey (1992)	Low-capacity modes	Medium-capacity modes	High-capacity modes
	one-way capacity/hr: 5,000 below	one-way capacity/hr: 5,000-30,000 (LRT, AGT, ALRT, monorail, Skybus, Maglev system)	one-way capacity/hr: 30,000 up
Chan (1994) Vuchic (2007)	Street transit modes	Medium-capacity modes	High-performance modes
	(RB, TB, SCR and tramway)	Semirapid Transit (BRT, LRT, AGT)	Rapid Transit (LRRT, ALRT, RRT)
Ministry of Transportation and Communications in Taiwan (1998)	-	Medium-capacity modes	-
	-	BRT, O-Bahn, AGT, LRT, LRRT	-

As mentioned above, the medium-capacity mode was defined differently in previous studies. Some described as street transit (Vuchic, 1981), some considered it to be semirapid transit (Chan, 1994; Vuchic, 2007), while others defined it by

different ranges of line capacity (Chang, 1987; Chang and Wey, 1992).

In this research, the reasons that “medium-capacity transit system” is used as the name for the group of alternatives (the transit systems for selection) are: (1) the decision support system (DSS) to be developed is aimed at helping decision makers choose a transit system which is more advanced than regular bus (RB) to provide more capacity with better performance such as speed, safety, and environmental protection; (2) although it is shown from previous studies that metro rapid transit (MRT) obviously has the best performance among all transit systems, its cost is relatively much higher than others and cannot be afforded in most areas especially for developing countries. Therefore, in this research, the term “medium-capacity transit system” refers to transit systems with capacities/performances between those of RB and MRT. That is, although there are some studies that consider LRRT and ALRT are not in the categories of “medium-capacity modes” (Chan, 1994; Vuchic, 2007), their capacities are generally in the range of 5,000 to 30,000, and their costs are certainly much lower than MRT. Hence, in this research, the alternatives used are mainly classified into two parts: advanced bus system and LRT system, which include BRT, O-Bahn, AGT as well as LRT, LRRT, and ALRT.

2.2 Comparative Studies for Medium-Capacity Transit Systems

2.2.1 Reviews of Attributes for Comparing Medium-Capacity Transit Systems

In reviewing previous studies, it is possible to group the comparisons of medium-capacity transit systems into four general periods.

In the early days, the comparisons were based on costs. Brems compared ‘Light

Rail Transit (LRT)’ and ‘Express Bus on busway’ based on functions of total costs established from line-acquisition cost and traffic cost, which used line output as a variable of these functions (Brems, 1980). After that, busway, light rail, and elevated rail (Skytrain) were modeled and compared by Spencer and Wang in a simple cost-benefit analysis which took time savings and costs savings into consideration (Spencer and Wang, 1996). In the research done by Sislak, he found that the cost-effectiveness of new start LRT lines in many smaller cities usually had poor performance because of their low demands. Hence, he compared and contrasted the costs, benefits (ridership estimates), and cost-effectiveness (annual costs divided by ridership) of the situations including No Build, Transport System Management (TSM), BRT as well as LRT (Sislak, 2000). Although the above studies did not compared only the ‘costs’ attribute, they did convert all attributes to cost and performed quantitative comparison between each type of medium-capacity transit modes. As follows, the studies mentioned above are presented in Table 2.2.

Table 2.2 Costs-based studies for comparing medium-capacity transit systems

	Brems (1980)	Spencer and Wang (1996)	Sislak (2000)
Alternatives	LRT Express bus on busway	Busway LRT Skytrain	TSM BRT LRT
Comparison standards	Total costs (TC)	Costs savings	Cost-effectiveness (CE)
Consideration	<ul style="list-style-type: none"> ✧ Line-acquisition cost (A) ✧ Traffic cost (verify with output value) (a) ✧ Outputs (Capacities) (X) ✧ $TC = A + aX$ 	<ul style="list-style-type: none"> ✧ Time savings ✧ Construction costs ✧ O & M costs 	<ul style="list-style-type: none"> ✧ Costs (C) ✧ Ridership (R) ✧ $CE = C / R$
Explanation	<ul style="list-style-type: none"> ✧ Traffic cost includes cost of O&M and vehicle-acquisition cost. ✧ Cost unit: dollars per line mile. ✧ Output unit: passenger spaces in both directions per year. 	<ul style="list-style-type: none"> ✧ The amounts of time savings are evaluated by comparing with the results of ‘no change’ situation and are transferred into money values. 	<ul style="list-style-type: none"> ✧ $C = C_{alter. i} - C_{no build}$ ✧ $R = R_{alter i} - R_{no build}$ ✧ Costs (C) include ‘capital cost’ and ‘O&M cost’ and are converted to annual base.

In the second period, people not only used cost-related attributes but also applied other attributes in evaluating and comparing medium-capacity transit systems (Kühn, 2002; McBrayer, 2003). Many attributes have been applied, including speeds, capacities, costs, waiting time, in-vehicle time, comfort, and understandability. Although these studies considered many attributes, the comparisons were done by considering each attribute separately rather than integrating these attributes together. Thus, there was still no study comparing medium-capacity transit systems by considering different attributes simultaneously and that could cause confusion to decision makers in the selection of a system.

Recently, many areas started to pay more attention to environmental issues, and the concept about sustainable development was also promoted worldwide. Previous studies showed that transportation activities caused significant damages to the environment, such as air pollution, noise, and global warming. Thus, to deal with these problems, many transportation-related studies included environmental attributes in the planning consideration. Studies about medium-capacity transit systems decision-making in this period also applied environmental attributes in their comparisons. For instance, Puchalsky used air pollution attributes including NO_x, VOC, and CO separately to compared BRT with LRT (Puchalsky, 2005), and Vincent and Jerram evaluated CO₂ emissions for system comparison (Vincent and Jerram, 2006). However, studies in this third period just considered environmental attributes rather than incorporating other types of attributes together.

Hence, in the fourth period, studies did comparisons between medium-capacity transit systems by considering many attributes including environmental issues. Currie compared local bus, BRT, and well-designed BRT to LRT using several

attributes, such as permanence, risk, capabilities, pedestrian access, noise, pollution, service frequency and speed, flexibility for choice, and convenience for transfer (Currie, 2006). However, in Currie's study, there was still some weakness in that he used qualitative rather than quantitative measures and did not integrate all the selected attributes together.

From the above review of past studies, we can find out that most of these studies did their comparisons of medium-capacity transit systems by using either a single attribute or a limited few attributes. Although there were some studies that used multiple attributes for comparison, the attributes were used separately and the analyses were just done qualitatively for comparison rather than integrating all attributes into a quantitative and objective value. In addition, we know that environmental consciousness and the concept of sustainability are in focus nowadays, so it is important to add environment-related attributes in the analysis. Hence, in this research, the environment-related attributes will be considered and integrated with all other selected quantitative and qualitative attributes together into a single quantitative value for comparison among medium-capacity transit systems.

2.2.2 Review of Methodologies for Comparing Medium-Capacity Transit Systems

The methodologies for comparing medium-capacity transit systems in past studies can be categorized into two approaches: The first approach involves merely a discussion of each compared alternative and then reach a conclusion for the comparison; and the second approach involves calculating quantitative measures which are used to rank the alternatives.

The methodology under the first approach typically takes more than one attribute into

consideration, and the comparison of the alternative systems is done by considering each attribute separately by way of discussion rather than ranking or integrating all attributes together. For example, Kühn (2002) compared BRT and LRT with a discussion of several attributes (cost, capacity, speed, development potential, and passenger satisfaction, etc.) one at a time.

The second approach can be further divided into four groups. The methodology in the first group usually compares only a single attribute for the alternative systems. For example, Brems (1980) compared LRT and express bus based on cost functions of the alternatives (shown in Figure 2.1). Sislak (2000) used “cost-effectiveness (annual costs divided by ridership)” as the basis for comparing the alternatives of ‘No Build’, ‘Transportation System Management’, ‘BRT’, and ‘LRT’.

Figure 2.1 Functions of Cost for Express Bus and Light Rail (Source: Brems, 1980)

The second group considers several system attributes, but each attribute is considered separately. Therefore, there is a rank for each attribute, but these ranks are not integrated in

the comparison of the alternative systems. For example, Puchalsky (2005) used several attributes (including NO_x, VOC, and CO) separately to compare transit systems (BRT and LRT). These transit systems are ranked on each attribute separately, rather than integrating all the attributes, for comparison.

The third group of methodologies can integrate two or more attributes together by transforming all attributes into the same measurement unit. This allows the values of all attributes for each alternative system to be combined into one value for comparison. For example, Spencer and Wang (1996) took time savings and costs savings into consideration for comparing busway, light rail, and elevated rail (Skytrain). They transformed time into cost units so that these two attributes can be integrated.

The fourth group integrates several attributes measured in different units together for comparing alternative systems. This group of methodologies is generally called Multi-attribute Evaluation (MAE). The candidate did not find any previous study in the literature that used the MAE method to compare medium-capacity transit systems. Chang and Wey (1992) used an Expert Decision Support System (EDSS) for comparing “rapid transit systems”, which included MRT, AGT, VAL, ALRT, LRRT, Skybus, Maglev, etc. EDSS combines an Expert System (ES) and a Decision Support System (DSS). The ES used the A.H.P method (which is a kind of qualitative MAE method) to consider several attributes simultaneously in comparing the alternative systems.

From this review of past studies, it is apparent that relatively few studies considered several attributes simultaneously in the comparison of alternative transit systems, and even fewer integrated these attributes into a single index. Therefore, the MAE method will be used in this study in order to consider several system attributes simultaneously and integrate

different types of attributes together.

2.3 Research on Selection of System Attributes

From the research alternatives stated, it is clear that the reasons for eliminating RB are its low capacity, speed, safety, and environmental effects; and that MRT is excluded due to cost concerns. Because these factors are those that formed the research targets, they are indeed important to be the attributes for comparing medium-capacity transit systems.

These factors can be generally classified into two groups: one is ‘performance’, which can be categorized into system performance and vehicle performance; and the other is ‘sustainability’, which can cover a wide range of issues including environmental effect, safety, costs, travel time, demand, and others. Therefore, the selected system attributes are divided in this research into ‘performance’ and ‘sustainability’. A more detailed discussion is provided in the following sections.

2.3.1 Performance

Transit system performance consists of a number of quantitative and qualitative elements. The quantitative indicators often used in measuring transit system performance include capacity, work, productivity, efficiency, consumption rates, and utilization. Among these indicators, ‘capacity’ was most widely used and it is defined as “the maximum frequency with which some objects can be transported on a line” (Vuchic, 2007). Vuchic also stated that “when only the term ‘capacity’ is used, it refers to the ‘line capacity,’ the maximum number of spaces transported on a line past a fixed point during one hour (Vuchic, 2007).” In addition, ‘reliability’ is

an important qualitative indicator for transit system evaluation and comparison. Therefore, in this research, the attributes of system performance to be used shall include ‘line capacity’, which is defined as “the maximum number of units (spaces) that can be transported on a line past a fixed point during one hour”, and ‘reliability’, which is used for evaluate the average on-time arrival rate of each transit system.

In addition to system performance, vehicle constraints are important for selecting transit modes because they might influence whether the selected transit system can operate normally or not. Minimum radius and maximum gradient of transit systems are the two most general and important attributes in considering vehicle constraints. If system planners ignore these two factors in system selection, it might lead to the chosen system fail to work properly or cause safety problems.

In conclusion, in this research, ‘line capacity’ as well as ‘reliability’ are selected to represent system performance, and ‘radius’ and ‘gradient’ will represent vehicle performance. These are then the attributes in the category of ‘performance’ attributes.

2.3.2Sustainability

Among the many definitions of ‘sustainable development’, the most oft-quoted one was that by WCED in 1987: “development that meets the need of the present without compromising the ability of future generations to meet their own needs.” (WCED, 1987)

Although transportation activities could bring convenience and improve economic development to people’s lives, it causes many environmental and social problems,

such as energy consumption, greenhouse emission, air pollution, noise, safety and congestion. In recent years, people start to face up to the non-sustainability caused by transportation, which led to more and more research in 'sustainable transportation'. Referring to Black's study, 'sustainable transportation' could be defined as "satisfying current transport and mobility needs without compromising the ability of future generations to meet these needs." (Black, 1996)

In the early days, studies on sustainable transportation were mainly aimed to the problem of environmental pollution. For example, Linster classified transportation sectors into water, rail, roadway, and air transport, and did a detailed analysis of the effects on environmental resources caused by the use of each of these transport sections (Linster, 1990). Whitelegg indicated that road transport, automobiles and trucks in particular, caused a long list of local and global problems including premature death caused by accidents and air pollution, excessive energy consumption, climate change, noise pollution, uprooting of inner-city neighborhoods, social isolation and class separation (Whitelegg, 1993). Black argued that the transport systems were not sustainable because petroleum reserves are finite; petroleum-based emissions are detrimental to air quality and the global environment; the use of motor vehicles destroys the ozone shield and produces excessive injuries and fatalities; many current transport facilities are congested; and, motor vehicle transport stimulates urban sprawl (Black, 1996).

In addition to environmental concerns, social and economic sustainability have also been mentioned as an important part of sustainability (Aalborg Charter, 1994; The World Bank, 1996). The Charter of European Cities and Towns towards Sustainability (the 'Aalborg Charter') stated that the objective of sustainable

development is “to achieve social justice, sustainable economies, and environmental sustainability (Aalborg Charter, 1994).” Litman and Burwell used a picture and a table to list sustainability issues and transportation impacts on sustainability, which also categorized sustainability into these three objectives (Figure 2.1 and Table 2.3) (Litman and Burwell, 2006). In addition, Steg and Gifford explained the meaning of the indicators for each objective: economic indicators should reflect possible effects on economic welfare, such as macroeconomic changes, GDP, economic efficiency, income distribution and unemployment rates; social indicators should measure effects on societal and individual quality of life, such as safety and health; and environmental indicators should appraise effects on environmental qualities, such as resource use, emissions and waste, and the quality of oil, water and air that may affect human and non-human life (Steg and Gifford, 2005). Chang stated that sustainable transportation policy includes not only economic and financial sustainability, environmental sustainability and social sustainability, but also governance sustainability (Chang, 2006).

Figure 2.2 Sustainability Issues (Source: Litman and Burwell, 2006)

Table 2.3 Transportation impacts on sustainability

(Source: Litman and Burwell, 2006)

<i>Economic</i>	<i>Social</i>	<i>Environmental</i>
Traffic congestion	Inequity of impacts	Air and water pollution
Mobility barriers	Mobility disadvantaged	Habitat loss
Accident damages	Human health impacts	Hydrologic impacts
Facility costs	Community interaction	DNRR
Consumer costs	Community liveability	
DNRR	Aesthetics	

DNRR: Depletion of non-renewable resources.

In a study by Greene and Wegener, the idea that the “equity” emphasized in sustainability covers not only the equity among generations but nations and individuals was brought up. Hence, if a society does not provide its members with minimum levels of subsistence, well-being, civil rights and justice, it cannot be called sustainable (Greene and Wegener, 1997).

In this research, we shall apply the concept that the objectives for achieving sustainability include economic sustainability, environmental sustainability, and social sustainability. Some selected attributes which can represent each type of sustainability will then be used to evaluate whether each of the medium-capacity transit systems are sustainability. For example, economic sustainability generally can be evaluated by system costs, revenue, and travel time; while the attributes of environmental sustainability can be air pollution, CO₂ emission, safety, congestion and noise.

2.4 Studies on Research Methodologies

2.4.1 Methods for Assessing Weighting

In the early days, there were three common techniques for weighting assessment: Eigenvector Method, Weighted Least Square Method, and Entropy Method (Hwang

and Yoon, 1981).

The Eigenvector Method was introduced by Saaty (Saaty, 1977). It is a method of scaling ratios using the principle eigenvector of a positive pair-wise comparison matrix. The process involves consulting an intensity scale of importance for activities (Table 2.4), completing a reciprocal matrix, and finally getting the weighting value from a system of homogeneous linear equations. This method is an understandable technique for weight assessment and is often applied in A.H.P method for building up the weighting for each criterion (attribute) weight based on the opinions of experts.

Table 2.4 Intensity scale of importance for activities (Source: Saaty, 1977)

Intensity of importance	Definition	Explanation
1	Equal importance	Two criteria contribute equally to the objective.
3	Weak importance of one over another	Experience and judgment slightly favor one criterion over another.
5	Essential or strong importance	Experience and judgment strongly favor one criterion over another.
7	Demonstrated importance	A criterion is strongly favored and its dominance is demonstrated in practice.
9	Absolute importance	The evidence favoring one criterion over another is of the highest possible order of affirmation.
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed.

A Weighted Least Square Method was proposed by Chu et al. (1979) to obtain the weight. Similar to the Eigenvector method, this method also makes use of an

intensity scale of importance for activities. A succession of mathematical inferential reasoning is then employed and the user can enter the relative importance values into a set of inferential linear equations to obtain the values of the weights. This method has the advantage that it is conceptually easier to understand than Saaty's eigenvector method as it involves only the solution of a set of simultaneous linear equations (Hwang and Yoon, 1981).

When the data of the decision matrix (the attribute values of all alternatives) are known, the Entropy Method may be applied to evaluate the weights. The term "entropy" can be considered synonymous to "uncertainty", and this concept is often used to investigate contrasts between sets of data. In an application of assessing weights, the weight of an attribute i would be decided by the similarity between each alternative's value in i . For example, when all the alternatives have similar values for a given attribute, then this attribute will not be considered as important. This also means if the values of this attribute for all alternatives are the same, then the attribute can be eliminated. This method can decide weights objectively from a given decision matrix, but the decision makers cannot decide the weights according to their opinions.

From the above review, the methods for assigning weights can be sorted into two types depending on whether the weighting is obtained from (a) subjective human opinions, such as the Eigenvector Method and Weighted Least Square Method; or (b) an objective decision matrix, for instance, the Entropy Method. To overcome the problem of deviations in the evaluation outcome from each type of methods, Chen (1989) developed a compromise weight evaluating method which considers the

subjective weights and objective weights simultaneously.

Since there is no evidence to believe that the importance of attributes is dependent on the values of a decision matrix, it is decided that this research will adopt the subjective way for weight evaluation. This means the system user's (decision maker or expert) opinions are considered to be more relevant in the selection of an appropriate transit system.

2.4.2 Multi-Attribute Evaluation

There are many Multi-attribute Evaluation (MAE) methods proposed by various researchers, and there are also different ways for classifying and integrating these methods.

In Hwang and Yoon's study, MAE methods are generally classified into three parts based on the situations of information given: one for 'methods where no preference information given'; another for 'methods with information on attributes given', and the third for 'methods with information on alternatives given'. The second type can be further divided in four ways: (1) standard level of each attribute, (2) relative importance of each attribute by ordinal preference, (3) relative importance of each attribute by cardinal preference, and (4) marginal rate of substitution (MRS) between attributes. The third type can also be sorted into two sections: pairwise preference given and pairwise proximity given. The classification of MAE methods by Huang and Yoon is summarized in Figure 2.2 (Hwang and Yoon, 1981).

METHODS FOR MULTIPLE ATTRIBUTE DECISION MAKING

- Methods for No Preference Information Given
 - ✓ Dominance
 - ✓ Maximin
 - ✓ Maximax
- Methods for Information on Attribute Given
 - ✧ Methods for Standard Level of Attribute Given
 - ✓ Conjunctive Method (Satisficing Method)
 - ✓ Disjunctive Method
 - ✧ Methods for Ordinal Preference of Attribute Given
 - ✓ Lexicographic Method
 - ✓ Elimination By Aspects
 - ✓ Permutation Method
 - ✧ Methods for Cardinal Preference of Attribute Given
 - ✓ Linear Assignment Method
 - ✓ Simple Additive Weighting Method
 - ✓ Hierarchical Additive Weighting Method
 - ✓ ELECTRE Method
 - ✓ TOPSIS
 - ✧ Methods for Marginal Rate of Substitution of Attributes Given
 - ✓ Hierarchical Tradeoffs
- Methods for Information on Alternative Given
 - ✧ Methods for Pairwise Preference Given
 - ✓ LINMAP
 - ✓ Interactive Simple Additive Weighting Method
 - ✧ Method for Pairwise Proximity Given
 - ✓ Multidimensional Scaling with Ideal Point

Figure 2.3 Classification of MAE methods by Hwang and Yoon (1981)

Feng and Chiou (2004) used another basis, the forms of attributes, to classify major MAE methods into four groups. One is ‘Qualitative’, which is used to deal with qualitative information evaluation. The second is ‘Medium’, which is between qualitative and quantitative, and evaluation by grades is the characteristic of this

method. The third one is ‘Quantitative’, which is for evaluating situations in which the criteria can be quantified. The last one is ‘Multicriteria Evaluation with Qualitative and Quantitative Data (MEQQD)’, which can consider both qualitative and quantitative criteria (Feng and Chiou, 2004). These four groups and their representative methods are charted by Feng and Chiou as shown in Figure 2.3:

Figure 2.4 Categories for MAE methods (Source: Feng and Chiou, 2004)

Among the MAE methods, the A.H.P method has often been applied in many transportation-related studies when data are obtained from questionnaires or other subjective opinions, such as expert systems (Chang and Wey, 1992), because the attribute form of such data is ‘Qualitative’ and A.H.P is a representative ‘Qualitative’ method. Apart from the A.H.P method, ELECTRE, TOPSIS, and MEQQD are also common methods used in transportation-related studies based on survey data forms.

For this research, considering that some of the selected attributes are presented in qualitative measures while others are in quantitative values, the MEQQD method would be an appropriate method because of its applicability for evaluating both two types of data. MEQQD is a multicriteria evaluation approach originally introduced by Voogd (Voogd, 1982) and improved by Feng (Feng, 1988) for mixed

‘quantitative-qualitative’ data. This method can be applied to evaluate alternatives, based on simultaneously considering quantitative and qualitative data, using the following procedures: (1) categorizing qualitative and quantitative criteria; (2) calculation of standardization of criteria score of quantitative criteria; (3) measuring the dominance level of each alternative by relative criteria scores between alternatives; (4) standardization of dominance level; and (5) calculating the appraisal score of each alternative and evaluating.

For this method, the establishment of standardization of criteria score of quantitative criteria considers merely the relativities between alternatives for the same attribute. However, it does not mean that the same standardization of criteria score for different attributes has the same meaning. Hence, MEQQD is not quite suitable for comparing alternatives with attributes which have different units. Therefore, another approach needs to be developed in this study to deal with the multi-attribute evaluation problem which involves both qualitative and quantitative attributes.

In addition, data for several attributes are typically expressed as a range rather than a specific value. Recently, some studies introduced the concepts of ‘grey theory’ into MAE methods to deal with the problem of uncertainty (Tao and Liu 2008). Hence, this study intends to deal with the problems of ‘quantitative’ and ‘qualitative’ data as well as uncertain data using the concepts of ‘grey’.

From the above introduction of MAE methods, to develop an appropriate decision support system (DSS) for comparing medium-capacity transit systems, we decide to apply concepts from existing methods for developing a more proper way which can

evaluate and compare alternatives by considering quantitative and qualitative attributes simultaneously. In additions, we want to apply grey theory into that evaluating way to deal with uncertainty situations.

2.5 Decision Support System

According to Sprague and Carlson, the concepts involved in DSS were first articulated in the early 1970's by Morton under the term 'management decision systems', and by Little's definition as a "*model-based set of procedures for processing data and judgments to assist a manager in his decision-making.*" After that, efforts were initiated to research and develop DSS, which became characterized as "*interactive computer-based systems that help decision makers utilize data and models to solve unstructured problems.*" (Sprague and Carlson, 1982)

Keen and Morton stated that "*DSS represents a point of view on the role of computer in the management decision-making process*", and it was also mentioned that decision support implies the use of computers to:

1. Assist managers in their decision processes in semi-structured tasks;
2. Support, rather than replace, managerial judgment; and
3. Improve the effectiveness of decision-making rather than its efficiency.

(Keen and Morton, 1978)

Moore and Chang argued that the structuredness concept, so much a part of early DSS definitions (i.e., that DSS can handle semi-structured and unstructured situations), is not meaningful in general. A problem can be described as structured

or unstructured only with respect to a particular decision-maker or a specific situation (i.e., structured decisions are structured because we choose to treat them that way). Thus, they defined DSS as extendible systems capable of supporting ad hoc data analysis and decision modeling, oriented toward future planning, and used at irregular, unplanned intervals (Moore and Chang 1980).

Bonczek et al defined a DSS as a computer-based system consisting of three interacting components: a language system, which is a mechanism to provide communication between the user and other components of the DSS; a knowledge system, which is like a repository of problem domain knowledge embodied in DSS as either data or procedures; and a problem-processing system, which is a link between the other two components, containing one or more of the general problem-manipulation capabilities required for decision-making (Bonczek et al, 1980).

Finally, Keen applied the term DSS “to situations where a ‘final’ system can be developed only through an adaptive process of learning and evolution.” Thus, he defined a DSS as the product of a developmental process in which the DSS user, the DSS builder, and the DSS itself are all capable of influencing one another, resulting in system evolution and patterns of use (Keen, 1980).

In general, the central purpose of DSS is to support and improve decision-making. And in later application, a DSS is usually built to support the solution of a certain problem or to evaluate an opportunity (Turban et al, 2005).

2.6 Conclusion

Based on the review of literature presented above, the following points can be noted:

1. The transit alternatives in this research consist of medium-capacity systems with a capacity in the range of 5,000 to 30,000 passengers per hour per way and a level of performance between those of regular bus and MRT. In this research, the medium-capacity systems are classified into two groups: advanced bus system and LRT system. The alternatives include BRT, O-Bahn, AGT, LRT, LRRT, and ALRT.
2. To the author's knowledge, there has been few comparative study of medium-capacity transit systems based on an evaluation of multiple system attributes simultaneously. It is the objective of this research to integrate the selected system attributes, both quantitative and qualitative ones, and consolidated these attributes values into a single quantitative value for comparing medium-capacity transit systems.
3. The system attributes to be used in this study will be grouped under 'performance' and 'sustainability'. The former includes line capacity, reliability, radius, and gradient, and the latter includes environmental sustainability, social sustainability, and economic sustainability.
4. To place due emphasis and respect on the opinion of the system user, the subjective assignment of attribute weighting.

5. Transit system attributes typically exist in both ‘quantitative’ and ‘qualitative’ forms and the quantitative attributes are usually in different units. As there is few existing method that can properly deal with such data, an approach will need to be developed in this research to deal with this issue. In addition, to take into account the situation that attributes values might be uncertain (for example, a range of values), the concepts of ‘fuzzy’ and ‘grey’ would be applied in this study.
6. Decision Support System can support and improve decision-making. It is usually built to support the solution of a certain problem or to evaluate an opportunity.

In conclusion, by taking into consideration the above points, it is hoped that the DSS to be developed in this study will have the ability to support decision makers in evaluating and comparing medium-capacity transit systems to arrive at a proper decision on the most appropriate transit system to implement.

CHAPTER 3 CHARACTERISTICS OF SELECTED ALTERNATIVE TRANSIT SYSTEMS

The procedure for selecting alternative systems had been discussed earlier. The selected alternatives which represent major medium-capacity transit systems for this research include BRT, O-Bahn, LRT, LRRT and AGT. In addition, the case of “Do-nothing” which means regular buses (RB) will still be used in the area rather than implementing a new medium-capacity transit system is also regarded as an alternative. In this Chapter, the characteristics of each of these alternative systems as well as the system infrastructure are described. For consistency, the material included come mainly from Vuchic (2007) which is supplemented by information from other references when appropriate.

3.1 Do-Nothing Alternative

A regular bus system, which uses buses and operates along fixed lines with fixed schedules, is by far the most widely used transit system. The typical RB services are street transit lines, which may represent the entire transit network (in small- and most medium-sized cities) or provide supplementary and feeder services to rail networks (in medium- and large-sized cities), and operate on streets with mixed traffic (ROW category C). The reliability of street transit depends on traffic conditions along its route, primarily congestion and various interferences, and its speed is lower than the speed of traffic flow due to time lost at transit stops.

3.1.1 Lines and Stations

A regular bus operates in mixed traffic on urban or suburban streets with no special

fixed facilities except bus-stop signs and benches or shelters. It requires virtually no investment, allows nearly any routing, but has adequate reliability only if other traffic on the same street does not have frequent delays. Given that regular buses are vulnerable to congestion and must make stops along the route, bus operating speed is always lower than the speed of private vehicles on the same facility.

As only the bus routes that will be replaced by a medium-capacity transit system are used for comparison with the alternative systems, it is assumed that the line length of these RB routes is the same as that of the other alternative systems, but the RB operates in mixed flow and may be impacted by other traffic. When a RB is on a street with smooth traffic, it may use any lane. But where traffic flow is heavy or when it has frequent stops, it usually stays in the curb lane.

3.1.2 Vehicle Size, Steering/Guidance and Propulsion

Line capacity, service frequency, operating costs, vehicle maneuverability, and riding comfort are factors for choosing the size of bus vehicles. Standard buses are the most often used in RB systems. The vehicle length is 10-12 m and can carry about 85 passengers per vehicle. Other types of buses are also deployed in some areas depending on requirements. For example, routes with low demand can use minibuses or midibuses. When the demand increases and the minimum headway is reached, line capacity could be further increased by using larger buses.

Three types of bus sizes are commonly used in RB systems: standard buses, articulated buses, and double-decker buses. Table 3.1 shows the characteristics of these buses. Regular buses are steered by drivers, and the most common propulsion

system is the diesel engine. Table 3.2 gives the steering forms of each type of regular buses. Besides, in recent years, compressed natural gas (CNG), liquefied petroleum gas (LPG), electric and hybrid propulsion systems can be applied in bus systems. Among these, CNG is a popular fuel used in bus propulsion.

Table 3.1 Sizes of Common Types of Regular Buses

Type	Length (m)	Seats	Capacity
Standard bus (low floor)	10 – 12	35 – 49 (28 – 35)	80 (60)
Articulated bus (usual status)	16 – 18	40 – 75 (35 – 60)	130 (100)
Double-decker bus (usual status)	10-12	60 – 95 (66)	125 (88)

Table 3.2 Steering Forms for Regular buses (Source: Vuchic, 2007)

Steering and Guidance Forms		Characteristics
Standard bus/ double-decker bus (two-axle)	Front-axle steering	Normal type
	Steering with both axles	The turning radius is shorter
Articulated bus	only front-axle steering (most articulated buses)	<u>Advantage:</u> engine may be placed in the rear which provides a somewhat more stable ride <u>Disadvantage:</u> turning radius is longer
	Steering with 1 st and 3 rd axles	<u>Advantage:</u> turning radius is shorter

3.2 BRT

Bus rapid transit (BRT) is a bus transit system (BTS) with higher quality, more efficient and attractive services than conventional bus. It has integrated vehicles, travel ways, stops/stations and operations which enable the system to provide much better performance than the conventional bus. These features require considerable dedicated space for roadways and stations which involve substantial investment in infrastructure and equipment.

The term “BRT” has caused considerable confusion and has been used for many projects that led to BTS only. As a consequence, this have resulted in a blurring and downgrading of the BRT concept. Vuchic (2007) listed six characteristics that a system needs to meet before it could be called “BRT”. These characteristics are:

1. The Right-of-Way (ROW) should be predominantly in Category B or Category A, not shared by other vehicles such as taxis or High Occupancy vehicles (HOVs). Only limited line sections, if any, with ROW C. (i.e. ROW: Strip of land with pavement or railroad track on which transit units operate. May be Category C – common streets with general traffic, Category B – partially separated but with crossings at grade, or Category A – fully separated and controlled by the transit agency.) (Vuchic, 2007)
2. Distinctive lines with frequent, reliable service and regular headways during all day hours.
3. Distinct stops/stations with good passenger protection, information, and fare-collection equipment, allowing fast passenger exchange. Stations should be spaced at least 300 m - 600 m apart in the central city and at greater distances in suburban areas.
4. Bus vehicles of distinctive design, with a large door channel-to-capacity ratio, low floor, or high platform for fast passenger exchange at stops and stations.
5. Bus preferential treatment at all major intersections.
6. Use of intelligent transportation system (ITS) technology for monitoring vehicle locations and movements, passenger information, and fare collection.

3.2.1 Lines and Stations

Bus lanes located along street curbs facilitate stopping at bus stops but the speeds in these lanes are slow and buses are often impeded by right-turning (left-turning in Singapore) vehicles. For BRT to be a distinctive system with priority over other traffic, the exclusive lanes are usually located at the centre portion of the roadway. Sometimes, exclusive busways or grade-separated roadways, which are the highest type of ROW for buses, are provided to improve BRT operating speeds as there will be no interference from other vehicles.

The number of lanes per direction depends on passenger volumes and lane capacity. To calculate lane capacity, one would need to know the BRT vehicle capacity, number of vehicles per unit time, and frequency. Also, the maximum frequency may be affected by traffic signal timing. Vuchic's (2007) indicated that the typical width of an exclusive single-lane roadway for BRT is 3.75 m, and that for an exclusive two-lane roadway for moderate bus speeds is 7.30 m. Exclusive two-lane roadways with high speeds would be much wider. A summary of lane widths for bus roadways is shown in Table 3.3.

Table 3.3 BRT Lane Width (Source: Vuchic, 2007)

Lanes with standard buses operation (m per lane)		Exclusive single-lane roadway	Exclusive two-lane roadways
<u>America</u>	<u>Most other countries</u>	3.75	✧ Moderate speed: 7.30 (two-lane) ✧ High speed (exceed 70km/h): 5.50 per lane + a medium separation or a physical divider + a shoulder on each side.
3.66 (standard)	3.50 (standard)		
3.05 (minimum)	3.00 (minimum)		

BRT stations are designed according to: the passenger volumes to be served, their access to stations on islands in the middle of the road, and fare collection method. The design details of BRT station for the two typical methods of fare collection is presented in Table 3.4.

Table 3.4 BRT Station Design for Different Fare Collection Methods

(Source: Vuchic, 2007)

Methods of Fare Collection	Details
Self-service fare collection	<ol style="list-style-type: none"> 1. Separate stops/stations can be provided for each direction. 2. Stop areas do not have to be fenced off.
Full payment control	<ol style="list-style-type: none"> 1. It needs to fence off the boarding platforms. 2. The design is much more difficult and takes more space. 3. Pedestrian access must be channeled via one or two pathways from intersections or overpasses to a set of fare gates. 4. Mostly using high platforms not only for faster boarding but also to prevent direct pedestrian access from the street.

3.2.2 Vehicle Size, Steering/Guidance and Propulsion

The size and capacity of a bus depends on the required line capacity, passenger comfort (seat/standee ratio), and desired service frequency. In general, BRT systems are served by articulated buses which provide high capacity and passenger comfort. In some cases, regular buses are used for lower demand or to provide higher service frequency for the same passenger volume. Sometimes, both regular and articulated

buses are used to provide higher capacity or service frequency than using only regular or articulated buses. In developing countries, major BRT lines have to handle very large passenger volumes and often need to use double-articulated buses lines to satisfy the demand (for example, Curitiba).

Similar to the RB system, BRT systems are generally steered by drivers. At present, guidance technology has not been applied on any BRT systems for normal operation, except for approach to station platforms. For a steered BRT bus, propulsion is typically by a diesel engine. Several newly propulsion such as compressed natural gas (CNG), liquefied petroleum gas (LPG), electric, and hybrid propulsion systems are used in recent years, which can reduce CO₂ emissions and air pollutions.

The sizes, capacities, and steering forms of BRT systems using standard buses and articulated buses are similar to those of regular buses (see Tables 3.1 and 3.2). Table 3.5, shows the characteristics of bi-articulated buses which are not used in RB systems. Table 3.6 presents the various methods used by BRT systems to approach station platforms.

Table 3.5 Size, Capacity, and Steering Form for Bi-articulated Buses

(Source: Vuchic, 2007)

Length (m)	Seats	Capacity	Steering
22 - 26	40 - 80	140 - 270	Has fourth axle steered to avoid excessively wide turning path

Table 3.6 Methods Used by BRT to Approach Station Platforms

(Source: Vuchic, 2007)

Methods	Description
Driver steering	As the bus approaches the platform, it slows down to 10 to 15 km/h and travels to the location where the bus doors match the platform doors or openings. No special technology is needed but considerable time is lost at each station. In some cases like Curitiba, gangplanks are lowered from the bus to bridge the gap.
Electronic guidance	Guidance is provided by an underground cable in the station area. The driver takes over steering again when the bus departs.
Optical guidance	Painted lines on the pavement are scanned and detected by the bus, giving it precise steering.
O-Bahn - type guidance	Guidance is somewhat more complicated, but its physical components prevent any other vehicles from entering the bus lane.

3.3 Guided Bus (Dual-Mode Bus)

A guided bus is a bus steered for part or all of its route by external means, usually on a dedicated track. The advantages of guided buses include: (1) it can operate independently in two modes using different sources of power with their relative advantages on different sections of the line, and these modes typically use electric power from overhead lines, tracks, or batteries, alternated with conventional fossil fuels steered on roadway; (2) sections of bus lines with guidance require narrower ROW, and they can provide greater safety and higher running speeds than conventional roadway or busway; and, (3) buses can be brought to a stop location precisely by guidance.

In practice, there are two main guidance categories. One is Kerb-guided busway (KGB), which is guided by kerbs (curbs) with guide bars on the sides, this is also called O-Bahn. The other is Rubber-tyred “tram”, which is guided by a central

guidance rail in the ground and propelled by electric power from overhead wires.

For Rubber-tyred “tram”, there are also two types of guidance technology: one is Guided Light Transit (GLT) developed by Bombardier and the other is Translohr developed by LOHRL. In the case of a GLT system, a single, double-flanged wheel between the rubber tires follows the guidance rail. Whereas in the Translohr case, it uses a special rail that is grasped by a pair of metal guide wheels set at 45° to the road and at 90° to each other. The different methods of guidance for KGB, GLT, and Translohr are shown in Figure 3.1. Among these systems, the Translohr system is intended for guidance-only operation and cannot be operated with fuel or steered. Hence, in this research, Translohr is eliminated and only KGB and GLT are considered as guided buses.

KGB	GLT	Translohr

Essen, Germany (1980) Adelaide, Australia (1986)	Nancy, France Caen, France	Clermont-Ferrand, France Tianjin, China

Figure 3.1 Guidance Methods used for KGB, GLT, and Translohr

3.3.1 Lines and Stations

In addition to the capabilities of a regular bus, a guided bus system can also operate

a special trackway. Thus, the line of a guided bus system may be treated as a combination of a bus system and a rail system. As a bus system, it can operate on roadways, exclusive lanes or busways. As a rail system, most guided bus systems can operate on an exclusive railway built in concrete while some can operate on a combined tramway/busway. Therefore, when it operates as a bus system, the line infrastructure is similar to that of a bus system (e.g. RB, BRT, exclusive busway, etc.). When it operates as a rail system, the line infrastructure is dependent on the technology used (e.g., KGB or GLT), and whether the railway of the guided bus system is combined with other tram railways.

As discussed earlier, the standard width of a BRT bus lane is 3.5-3.66 m, and the width of a two-lane roadway for moderate speeds should be above 7.30 m. Smiler (2001) indicated that the typical width of a two-lane road for driver-steered standard buses is 7.5-8 m, while the dedicated busways used by a mechanically guided bus only needs to be a little wider than the bus itself. For example, a two-way busway needs only to be 6 m wide. Table 3.7 shows the required bus lane width for a Kerb guided bus (KGB) and a steered bus.

Table 3.7 Bus Lane Width for Driver-Steered Bus and KGB Bus

(Source: Smiler, 2001)

Transit Systems	Considerations for Lane Width	Width (for 2.5-2.55 m wide standard bus)
Standard bus steered by drivers	To allow for driver-steered buses to ✧ “wander” sideways slightly, and ✧ still pass safely when travelling at a moderate speed	Two lane road: at least 7.5-8 m
KGB using standard bus	The lanes only need to be a little wider than the bus itself.	Two-way busway: 6 m

Similarly, the stations of a guided bus system may also have a bus system portion and a rail system portion. Stations for the bus system portion can be designed as bus stops for regular buses or stations for a BRT, depending on the system design. For the rail system portion, the station spacing is longer than that of other bus systems in order to operate at higher speeds. In addition, a rail system station is often built as an interchange or a terminal station. Hence, stations in the rail portion of a guided bus system are generally important and well- designed. Take Adelaide's O-Bahn system as an example, the stations in the rail portion include large bus interchange space and car parks, and the scales of stations are similar to those of a regional rail or MRT system with ROW A, which include complete facilities such as fare collection machines, barrier-free facilities, platforms with adequate waiting space, etc.

3.3.2 Vehicle Size, Steering/Guidance and Propulsion

The factors that affect the size of a guided-bus vehicle are similar to those for a BRT system: line capacity requirement, comfort (seat/standee ratio), and desired service frequency. Clearly, these factors vary from one system to another depending on site-specific requirements.

For KGB systems, standard buses and articulated buses are usually used in most areas, and double-decker buses are sometimes used (e.g., Birmingham and Leeds). Although, Germany has developed versions of 'double-articulated' bus, these are more conceptual prototypes than actual vehicles in service. These vehicles can only be driven by electric guidance using overhead wires (e.g. Mercedes-Benz 0 305 G2) rather than operating as two modes. All vehicles in the GLT Bombardier system are

the same: 24.5 m long double-articulated buses with forty seats and 105 standing spaces per vehicle.

A guided bus is generally a dual-mode bus and can be operated by steering or by guidance from different sources of power on different sections of the same line. When it is operated by steering, a guided bus is no different from a conventional bus. When it is guided, the guidance system can be either physical or remote (e.g., optical, magnet, or radio guidance). At the present time, systems with remote guidance are still in the development stage, and physical guidance is used by all systems. Physical guidance can be provided by “kerbs” (guide bars on the sides, such as the O-Bahn system) or “central metal wheels”. The latter is basically a Rubber-tyred “tram” (e.g., Translohr and GLT).

A guided bus usually can be operated by two modes and can therefore be propelled by two forms of energy. Typically, electric power (derived from overhead wires, third rail or batteries) is used when the system is guided on rail, while fossil fuel is used when it is steered by driver on busways or other roadways.

3.4 LRT

LRT was first developed by upgrading streetcars (tramways). Although the two systems have overlapping characteristics, a LRT system is very different from a typical streetcar system. Vuchic (2007) identified some main elements that a rail system must have in order to be called LRT:

- LRT will have mostly ROW B or A, as compared to ROW C and B for streetcars.

- Track crossings at streets are signalised, usually with priority in signal control.
- Stops/stations are separated from street roadways, with passenger protection, amenities, and information.
- Average spacing of 300 - 600 m between stops/stations.
- Vehicles are articulated, high-capacity units often operated as two- to four-car units.
- Vehicles have multiple doors and low floors or high platforms for easy and rapid access; they are spacious, with a comfortable, quiet ride.
- Maximum speeds of 70 km/h or higher, with protected grade crossing in the latter case.
- High-quality ROW, particularly in tunnels, and often designed with provision for possible later conversion to metro.

As with streetcars, LRT can run on streets and mix with road traffic and pedestrians. Thus, it has the ability to utilize all ROW categories and yet have the advantages of guided technology: high capacity and labor productivity, comfortable ride, distinct image, permanence, etc. A typical LRT network usually has tracks on fully separated sections or along arterial streets. In the case of the latter, tracks are located in road medians, and cross at-grade intersections with preferential signal timing. If LRT passes through high-density city areas, it may use tunnels or operate in traffic-free zones or even pedestrian malls. The lower noise and pollutant emission, as well as a better safety record make LRT more compatible with a pedestrian environment than buses.

3.4.1 Lines and Stations

LRT is a mode with ROW categories B and A for 70% to 90% of the total network length. In exceptional cases, there may be some portion on ROW C. It can travel in street medians, tunnels, through parks and pedestrian zones, on the same line. In the central city area or along congested arterials, it is common practice to separate the most critical sections to eliminate sources of service disturbance. Hence, in very high-density cities, tunnel sections are used for LRT systems which greatly enhance the quality of service. While in other areas, LRT penetration into the CBD area may be on an at-grade alignment through pedestrian areas. In medium-sized cities such an arrangement often contributes to the livability of pedestrian zones. Outside the central core area, LRT is usually placed on ROW category B.

The flexibility in alignments of LRT systems allows a staged upgrading of a rail network to a new ROW without service interruption and with immediate utilization of new route sections. Such staging permits investment to be tailored to local conditions, desired service quality, and the availability of capital funds.

Due to the advantages mentioned earlier, LRT networks are characterized by fairly good coverage of central areas (in tunnels, aerial ways, or on at-grade separated ROW) with extensions branching out at-grade on a number of radial routes. As LRT vehicles are driven by guidance, the lanes only need to be slightly wider than the vehicle itself (about 2.20 - 2.80 m). The typical width of an exclusive lane for LRT ranges from 3.40 to 3.60 m (Vuchic 2007).

Factors considered in station design for a typical LRT are similar to those for BRT:

projected passenger volume, service frequency, passenger access (whether station is on the road median), length per transit unit, and fare collection method. Normally, LRT systems use self-service fare collection. Hence, if LRT runs in the street median, separate stations/stops would be provided for each direction, and station/stop areas do not have to be fenced off. Such stations/stops have low platforms so that pedestrian can easily cross at grade level, and it can be constructed easily with low investment costs. Depending on the type of vehicles used and the location of the station, some LRT stations do use high platforms. Average LRT station spacing is 500 to 1000 m, but reduces to 400 - 800 m, on average, in central areas.

The facilities available at LRT stations depend on the design and demand at each station. They usually include platforms, shelters, chairs, and fare collection machines. In addition, at major stations such as interchanges and terminal stations, elevators, information display, bus interchanges, carparks for Park-and-ride (P+R), waiting areas for kiss-and-ride (K+R) may also be provided. P+R and K+R access modes are becoming popular, particularly on new North American LRT systems such as those in St. Louis, Los Angeles, and Sacramento.

3.4.2 Vehicle Size, Steering/Guidance and Propulsion

LRT vehicles may have two to seven articulated sections. They are usually operated by articulating two- to four-sections per transit unit (TU) depending on passenger demand. The length of an articulated LRT TU ranges from 18 to 42 m.

LRT lines are guided on rail, and they can be operated either by drivers or by automatic control depending on system technology and the areas where routes pass

through. New LRT systems can be driver-operated in crowded areas, and switched to fully automatic operation on ROW A line sections (e.g. San Francisco). LRT is an electrical-power propelled rail system, but it still has high acceleration-deceleration capabilities ($1\text{--}2\text{ m/s}^2$, emergency braking 3.0 m/s^2) to deal with some unexpected situations.

3.5 LRRT and AGT

Light rail rapid transit (LRRT) is the highest-performance form of LRT. It resembles a small-scale rapid transit system: vehicles are very similar in size and design to LRT vehicles but only operate on fully exclusive ROW at high speeds. It is used in areas that require high performance, but do not have the high passenger volumes to justify a MRT system. Only a few of such systems are in operation at present (e.g. Norristown Line in Philadelphia and Manila Metro). However, its significance has increased greatly with the availability of full automation (which can also be called Automated Light Rail Transit or ALRT). The ability to operate trains without crews allows frequent service with shorter trains, thereby making service attractive to passengers even for moderate volumes.

ALRT is often considered for LRRT systems. However, there are some overlaps between ALRT and Automated Guided Transit (AGT) systems in that both are electric-powered, guided, fully automated modes. Although LRRT systems are usually guided by steel wheels on rails while AGT systems are mostly guided by rubber tires, both are propelled by electric power with fully automated operation on exclusive ROW, and have similar performance. Therefore, LRRT, ALRT and AGT belong in the same transit category in this research, and are classified into two

forms of systems: (a) LRRT with drivers, and (b) ALRT and AGT by fully automated operations.

3.5.1 Lines and Stations

As mentioned, LRRT, AGT, and ALRT lines all have exclusive ROW, or only a few at-grade crossings with full preemption, regardless of the degree of automated operation. Due to concern on costs and land requirement, they are usually elevated instead of underground or at-grade. Because of its exclusive ROW, operations can be conducted at higher speeds, and reliability is much better than BRT and LRT which may not have exclusive ROW for some portions of the system. In addition, fully automated ALRT and AGT systems operate without crews which enable frequent service with shorter trains. This reduces passenger waiting time and makes the service more attractive.

These systems usually have stations that are provided with more complete facilities for passenger boarding/alighting, waiting, and transfer. Since the way facilities of these systems are usually elevated, the station facilities include not only platforms and fare-collection equipment but also stairways, elevators and escalators. Some areas operate an elevated light rail system as a metro rail transit (MRT) system, so the stations may have facilities similar to the MRT stations.

Similar to other transit systems, the factors that affect station design include passenger volumes, system frequency, and length per TU. At some stations, there may be concerns on staircase congestion as well as security. In addition, some LRRT/ALRT/AGT stations are also transfer stations for passenger transfers to other

lines or other modes. For such stations the design should also take into account passenger routing for transfers, the number of transit lines calling at the station, and the access arrangement for other transportation modes.

3.5.2 Vehicle Size, Steering/Guidance and Propulsion

The size of the transit unit (TU) clearly depends on passenger demand and required/desired service frequency. The size of a typical LRRT vehicle is similar to that of a LRT system, typically between two to four vehicles per TU and 18 to 42 m long. For systems that are fully automated without crew, the size per TU can be shorter so as to provide higher service frequencies. For example, the length of AGT vehicles per TU is usually about 26 m and consists of two sections.

LRRT and ALRT are guided by steel wheels on rail. Although AGT systems operate on rubber tires, they have other guidance mechanisms which defer according to vehicle type. For example, the Bombardier CX-100 vehicles are guided by eight small horizontal tires running along a vertical steel I-beam in the center of the guideway. Almost all LRRT, ALRT, and AGT vehicles are propelled by electric power from the third rail.

3.6 Comparison for the Selected Alternative Systems

In this section, the analysis, synthesis and comparison for the selected alternative systems are done by a table to conclude the introduction of the characteristics of selected alternative transit systems in this chapter, which is shown in Table 3.8.

Table 3.8 Comparisons for the Selected Alternative Systems

	Do-Nothing (Regular Bus)	BRT	Guided Bus	LRT	LRRT and AGT
ROW	Typically in C	Often in B or A	Often in B or A	Usually in B or A	A
Reliability	Low to medium	Medium	High	High	Very High
Operating Speed	Low	Medium	Medium to High	High	Very High
Route	Almost any route	Usually on a bus lane, sometimes on roadway	Usually on a dedicated track, can also be steered on roadway (dual modes)	Usually on a dedicated track, also can be on an at-grade alignment through pedestrian areas.	Always on a dedicated track
Steering/ Guidance	Steered by driver	Steered by driver	Steered by driver or guided on track	Guided on rail by driver or automatically	Mostly automatic guidance, but some guided by driver
Vehicle Size	Mostly standard bus	Mostly articulated bus	Mostly articulated bus	Articulated (typically 2- to 4-car units)	Articulated (typically 2- to 4-car units)
Capacity	Standard Bus: 60	Articulated bus: 100	Articulated bus: 100	100 to 250	100 to 250
Propulsion	Typically by diesel	Typically by diesel	Guided: electric Steered: diesel	Electric	Electric
Station Facility	Simple	Simple to medium	Medium	Medium	Full
Investment	Virtually no	Low	Medium	High	Very high
Passenger Protection	Low	Medium	High	High	Very high
Comfort	Low	Low to medium	Medium	High	High

CHAPTER 4 STUDY APPROACH AND METHODOLOGY

The literature reviewed in Chapter 2 and the descriptions of the characteristics of the selected alternative medium-capacity transit systems in Chapter 3 provide the background knowledge for this research. Both would contribute to the formulation of an approach and the methodology needed to develop a decision support system (DSS) that could achieve the stated objectives of this study.

In past studies that aim to assist in the selection of alternative transit systems, the evaluation was typically based either on a single attribute or using several attributes but the comparison was made separately for each attribute. In this research, a DSS to help transit planners and decision makers in the selection of the most suitable medium-capacity transit system will be developed by evaluating simultaneously multiple attributes in the comparison of alternative transit systems. Transit planners can use the DSS to evaluate and compare alternatives and obtain the recommendation from the DSS to let decision makers making decision. In addition, environmental issues are now gaining importance and sustainable development is becoming a significant objective for transit systems. Therefore, the DSS will evaluate quantitative as well as qualitative factors relating to both performance and sustainability, such as line capacity, reliability, costs and revenues, time, congestion, air pollution, etc.

In order to develop a good DSS for selecting an appropriate transit system, it is important to understand the major system attributes on which the selection will be based. Therefore, it is pertinent to first discuss the attributes selected for evaluating the alternative transit systems.

4.1 Definitions of Selected System Attributes

As discussed in Chapter 2, *Performance* and *Sustainability* are the main categories of system attributes to be used in this research. The *Performance* category can be further classified into ‘System performance’ and ‘Vehicle performance’. The *Sustainability* category can also be further classified into ‘Economic sustainability’, ‘Social sustainability’, and ‘Environmental sustainability’. The following sections describe the selection of system attributes in each of these categories for comparing alternative transit systems in the DSS to be developed.

4.1.1 Performance

4.1.1.1 System Performance

Line Capacity (C) is the maximum number of transit units that can be transported on a line past a point in an hour under a given set of conditions. Depending on the measurement unit used, it may be called *line capacity in TUs*, *vehicle line capacity* or *maximum offered line capacity*. The most often used is *maximum offered line capacity* which is measured in passenger spaces per hour and represents the maximum capability of a transit line to transport passengers. Hence, it is often referred to simply as ‘line capacity’ (Vuchic 20007) and is computed as the product of *vehicle line capacity (c)* and *vehicle capacity (C_v)*. That is,

$$C = c \cdot C_v = f_{max} \cdot n \cdot C_v = \frac{3600n \cdot C_v}{h_{min}} = \frac{3600n \cdot C_v}{Max(h_{w min}, h_{s min})} \quad (4.1)$$

Where *c* is the maximum number of vehicles that can pass a fixed point per hour

$$c = f_{max} \cdot n \quad (4.2)$$

In the above, f_{max} is the maximum frequency which is the maximum number of TUs that can pass a fixed point per hour (or line capacity in TUs), and n is the number of vehicles per TU.

Frequency is the inverse of service headway, h , which is the time interval between two successive TUs. Maximum frequency is determined by the shortest headway. There are two different headways associated with most transit lines: *way headway* for line sections without stations, and *station headway* representing the time interval between successive TUs at stations. Hence, the maximum frequency that can be achieved on a transit line is determined by the larger of the minimum way headway ($h_{w\ min}$) and minimum station headway ($h_{s\ min}$) as shown in Eq. (4.3):

$$f_{max} = \frac{3600}{h_{min}} = \frac{3600}{Max(h_{w\ min}, h_{s\ min})} \quad (4.3)$$

Reliability performance is measured by percent of on-time (typically within 4 minutes of schedule) arrivals at a station. Reliability depends on three major factors: (1) ROW control is the most important one; (2) train departure control, which determines the length of dwell time at stations and hence adherence to schedule; and (3) the technical reliability of the equipment. It is difficult to estimate the reliability of a transit alternative quantitatively before it is operated. Therefore, a qualitative rating is used. Vuchic (2007) rated the reliability of alternative systems as follows: Regular bus is rated ‘low to medium’, BRT is rated ‘medium’, LRT is rated ‘high’, and LRRT and AGT are rated ‘very high’. In this DSS, transit system reliability is rated on a scale of 10 (see Figure 4.1). The higher the value, the more reliable is the transit system. Hence, a value of 10 is associated with the most

reliable transit system, and a value of 0 with the most unreliable system. The assumed scales for rating of alternative transit systems are as follows:

Figure 4.1 A Way for Qualifying the Reliabilities of Alternatives in the DSS

Travel Time is used to compare the efficiency of alternative systems in the DSS. Here, travel time refers to the average travel time that passengers need to spend by using a specific transit system for their trips. A system is deemed more efficient if it provides faster services to passengers. Travel time using public transit generally consists of three components: access/egress times, waiting/transfer time, and in-vehicle time (IVT). Access/egress times refer to the time spent getting to and leaving from the transit service, either by walking or by using a vehicle. For a medium-capacity transit system, this typically means walking instead of using a vehicle because the transit stop/station spacing is usually small. Hence, access/egress times in this research is determined by a passenger's walking distance and his/her walking speed. Waiting/transfer time is the time passengers spend waiting to board after they have arrived at the transit station/stop. This depends on the frequency of service and is, on average, half the headway of the transit service. Finally, IVT varies according to speed, acceleration, deceleration, distance between stations, and interference to departure (for at-grade systems), and it is usually calculated as average distance divided by operating speed.

All alternative transit systems have the same average walking distance since transit line/network and station/stop locations are the same for all alternatives. In addition, average walking speed also would not vary which means access/egress times are the same for all alternative transit systems. Nevertheless, access/egress times will be computed so as to arrive at estimations of total travel time. From the literature (for example, O’Sullivan and Morrall, 1996; Chu, 2008), average walking distance is typically about 500 m from origin to station or from station to destination, and average walking speed around 1.29 m/sec (see Tables A.6 and A.7 in Appendix A). A summary of these travel time components is given in Table 4.1.

Table 4.1 Estimation of Travel Time for Alternative Transit Systems

Travel Time	Description
Access/egress Times	$2 * 500 \text{ (m)} / 1.29 \text{ (m/sec)} \approx 6.5 \text{ (min)}$ (4.4)
Waiting/transfer Time	$(\text{average headway}) / 2$ (4.5)
In-vehicle Time (IVT)	$(\text{average riding distance}) / (\text{average operating speed})$ (4.6)
$AT_{Ai}^A = (T_{\text{walk}} + T_{\text{wait } i} + T_{\text{IVT } i})$ (4.7) where, AT_{Ai}^A = Average travel time of alternative system i, minutes/passenger $T_{\text{walk } i}$ = Average walk and access times of alternative system i. $T_{\text{wait } i}$ = Average waiting time of alternative system i. $T_{\text{IVT } i}$ = Average in-vehicle time of alternative system i. Note: average travel distances of alternative systems are assumed to be the same when they are compared on the same line.	

4.1.1.2 Vehicle Performance

Curvature (radius of curve). Minimum turning radius is the radius of the smallest circular turn that the vehicle is capable of making. As vehicles have different wheelbase structures, the minimum turning radius for each transit system may differ. It is possible that the curvature of routes designed by planners for one

medium-capacity transit system may not be appropriate for other alternative systems. Hence, the curvature attribute is used to evaluate whether the planned radius of curve on the proposed route is suitable for an alternative system. In this respect, this attribute is not meant for comparing alternative transit systems but for selecting all feasible systems for the planned curvature on the proposed route. Table 4.2 gives the default values of minimum radius of each alternative system.

Table 4.2 Default Values of Minimum Radius of Transit Systems

Transit System	Regular bus	Guided Bus	BRT	LRT	LRRT	AGT
Min. Radius (m)	10	60	13	20	25	50

Gradient is the slope (in percentage) of a transit route. Each system has a maximum gradient which would depend on the friction between vehicles and the way facility, vehicle weight, etc. The planned gradient of a proposed route may be too steep for some transit systems. As in the case of curvature, this attribute is not meant for comparing transit systems but for evaluating if a transit system can operated on the planned gradient for the proposed route. Table 4.3 presents the default values of maximum and desired gradients of alternative transit systems.

Table 4.3 Default Maximum and Desired Gradients of Transit Systems

Transit System	Regular bus	Guided Bus	BRT	LRT	LRRT	AGT
Maximum Gradient	19%	7%	12%	8%	8%	8%
Desired Gradient	15%	6%	10%	6%	7%	7%

4.1.2 Sustainability

As mentioned earlier, sustainability can be grouped into economic, social, and

environmental sustainability. This classification will be used in selecting the attributes for comparing transit systems. There had been some past studies on the evaluation of transport-related sustainability. Most were conducted for a specific area, for example, UK (1999) and Taipei (1996). Very few studies evaluated the sustainability attributes of specific transport systems. One such study was by Hsu and Liu (2004). The indicators or attributes used in these studies can be found in Appendix A (Tables A.1 to A.3). Based on the indicators used in these studies, a set of preliminary sustainable system attributes appropriate for comparing medium-capacity transit systems was compiled. Table 4.4 summarizes this preliminary set of attributes for use in this study. In the following sections, each of these attributes will be discussed which will then lead to the final selection of system attributes for developing the decision support system.

Table 4.4 Preliminary Set of Attributes for Sustainability Evaluation

Categories	Attribute / Indicators
Economic Sustainability	Costs
	Revenues
Social Sustainability	External costs
	Accessibility
	Mobility
	Access difficulty to the disabled
	Congestion
	New retail floorspace (increased business opportunities)
	Safety
Environmental Sustainability	Energy consumption
	CO ₂ emission
	Air pollution
	Noise

4.1.2.1 Economic Sustainability

Costs consist of fixed and variable costs. Transit system costs include investment or capital costs and operation and maintenance costs. Investment costs usually mean costs before the start of operations, and are not affected by the capacity provided by the system. Brems (1980) developed linear cost functions for both LRT and busway system by relating costs to output (defined as the annual passenger spaces provided by a transit system in both directions). In that study, the fixed costs were referred to as *line-acquisition cost*, and the variable costs were called *traffic cost*. The latter was further divided into *vehicle acquisition cost* and *operation and maintenance cost*. Table A.4 in Appendix A provides more details on these costs definitions. Vuchic (2007) classified transit system costs into two types: *investment costs* and *operation and maintenance costs* to represent the fixed and variable costs. Table A.5 in Appendix A provides more details on these costs.

The definitions of costs used for the DSS here are similarly to those by Vuchic with additional ones to give better coverage (see Tables 4.5a and 4.5b). Since costs may be measured in different units, it is important to convert all costs to the same unit. To simplify comparison between transit systems, *total annual system cost* is used in this study. Given that the time periods for planning, construction, and design life for each transit system may be different, *total annual system cost* refers to the system's total costs from the start of planning to the end of the system's design life divided by the design life. All cost values are expressed in present (i.e., base year) value.

Table 4.5a Cost Components Considered in the DSS – Investment Costs

Item		Inclusion	Comment
Planning and Design		All planning and design costs	Default: 5% of direct construction
ROW acquisition		Land purchases for ROW	No direct cost if underground or use of public ROW.
		Land purchases for station space	
Direct construction	Permanent way	Preparatory works (e.g. removal of objects or buildings, utility relocation)	Elevated structures: 2 to 3 times higher than at-grade.
		Line infrastructure	Underground: at least 2 to 3 times more expensive than elevated structures.
		Restoration of street and sidewalk	
		Construction of plazas and landscaping	
	Track superstructure	Tracks, switches, crossovers, and related equipment	-
	Station	All station construction costs (platforms, walkways, stairways, escalators, fare collection, barrier, corridors, parking lots, etc)	Vary by mode and position relative to location, type (underground, at-grade or elevated), and surroundings.
	Power supply	Substations, distribution system, third rail or overhead wire	-
	Control and communication	Signaling system, telephone and other communications, and emergency systems	-
	Maintenance and storage facilities	All facilities for maintenance and storage in that system, including shops, yards, and administrative facilities	Depends on site location and shape, type of maintenance to be performed, and capacity.
Indirect construction		Vehicle	Depends on complexity, design, and number of vehicles ordered.
		All agency costs during implementation of the facility, such as administration, engineering management and supervision, air pollution control fees, environmental monitoring fees, etc.	-
Contingencies		Unpredictable costs	10% - 25% (default: 15%) of direct construction costs

Table 4.5b Cost Components Considered in the DSS – Operating, Maintenance and Replacement Costs

Cost Type	Item	Inclusion
Operating and Maintenance	Power	Costs of electricity or fuel
	Vehicle operations	Wages of all personnel involved in operation, such as drivers, supervisors, station attendants, and scheduling personnel
	Vehicle maintenance	Expenditures for personnel and material necessary for the maintenance, repair, testing and cleaning of cars.
	Permanent-way maintenance	Costs of personnel and material required to maintain the permanent way, including tracks, power supply, signals, etc.
	General and administration	Indirect operating costs (management, legal services, accounting, insurance, employee benefit, building & ground maintenance, and miscellaneous costs)
Replacement		The facilities need to be replaced if their economic life is shorter than the system's operating period.

The user needs to input the costs of each alternative transit system. Note that the costs of *vehicle/equipment purchase and replacement* as well as *operating and maintenance (O&M) costs* would depend on passenger demand. Hence, the user would need to know the variation of these costs with changes in demand. In addition, some cost components may be estimated by *direct construction costs* such as *planning and design costs*, *indirect construction costs*, and *contingencies*. The values of all other cost components are not affected by demand.

The costs of *vehicle purchase* can be estimated by using design hour volume. This is the one-way passenger demand among all sections of the line at the 30th highest

volume hour of the year (P_{max}), and is usually used to represent system demand. The same applies to *vehicle replacement cost*. If a network with several lines is planned for an area, *vehicle purchase costs* are estimated from the sum of the P_{max} for all lines in the network. The *O&M costs* are assumed to be directly related to the number of passenger trips. That is, the *O&M costs* of an alternative transit system at any demand level (i.e., total passenger trips) can be calculated if the *average O&M costs per passenger trip* of this system is known.

Revenues can generally be classified into two parts: fares and other revenue. Fare revenue depends on fare structure (eg. flat fare, zonal fare, etc.), fare per unit travel, and passenger O-D distribution; while other revenue includes income from all other sources such as advertising, interest and investment, rental, concessions, consulting, etc. The common revenue items of a transit system can be shown as Table 4.6.

Table 4.6 The Revenue Types and Items of a Transit System

Revenue Type	Item	Description
Fare Revenue	Fare	Passenger fare which depends on ridership and fare schedule.
Other Revenues	Advertising	In vehicle: (e.g., ring pull, windows, walls, doors) In station: (e.g., stairs, escalators/elevators, corridors, platforms)
	Investment	
	Rental	Example: concession stalls or stores in stations.
	Land/property development along transit line	
	Consulting	Consultancy work for other cities or countries which are less experienced in the managing/operating transit systems.
	Others	All other revenues not included in the above items.

In this study, the best way for the calculation of the total revenue of the transit alternative is to input each value of the revenue items which are shown in Table 4.6.

If the revenue items cannot be obtained, the user can just input the *fare revenue*, and the DSS will use the default value for *other revenues* to calculate the total revenue.

The default value is decided by the following way: From the 2007 annual reports of Singapore's SMRT Ltd (SMRT, 2007) and SBS Transit Ltd (SBS, 2007), and Metro Taipei (TRTC, 2007), *other revenue* for these three transit operators amounted to 5%, 8%, and 14% of the fare revenue, respectively. The *average other revenue* as a percentage of fare revenue is 9% for these operators. This percentage is set as the default value of other revenue (as a percentage of fare revenue) in the DSS. The unit of measurement is dollars per year. Users have to input 'total fare revenue per year' and 'other revenue per year' or 'other revenue as a percentage of total fare revenue'. The total revenue per year is therefore the sum of these two revenue components.

Similar to the "costs" attribute, revenues are also assumed to be directly related to the number of passenger trips, and revenue at different demand levels can be estimated if the *average revenue per passenger trip* is known.

4.1.2.2 Social Sustainability

External Costs. An external cost is a negative impact on any party not directly involved in an economic decision. For a transport system, the external costs caused by the system are costs borne not by the users of the system but by others. In other words, it is the burden which is imposed by transport-related activities on non-users. These generally include the external costs of congestion, accident, air pollution, climate change, noise as well as impacts on nature and landscape. In addressing social sustainability, external costs are often used to evaluate the negative impacts

to society caused by a given transport system. Often, these external costs are calculated by combining all the factors such as congestion, accident, air pollution, climate change, noise, etc. into a monetary unit.

Although the use of a medium-capacity transit system leads to some external costs, the associated reduction in the use of private vehicles would result in reductions in other external costs. Hence, some external costs such as CO₂ emission, air pollution, and congestion can be thought of as “benefits” from the provision of a medium-capacity transit system. It should be noted that it is difficult to express some of the external costs (e.g. air pollution and noise) in monetary units due to differences in perceptions, feelings and wage levels among people. Consequently, it may not be appropriate to use willingness-to-pay to estimate these costs, and it may be better to express these factors in qualitative or quantitative terms.

The factors that impose external costs included in this study are congestion, energy consumption, global warming (greenhouse effect), air pollution, noise, and safety. These factors are grouped and discussed either under environmental sustainability or social sustainability. Therefore, the ‘external costs’ attribute is not evaluated explicitly as a separate attribute in this research.

Accessibility is the ability to reach desired services, activities and destinations. Accessibility is also the goal of most transport activities except the small portion of travel for which mobility is an end in itself (e.g., jogging, cruising, leisure train rides). Even recreational travel will usually have a destination, such as a resort or campsite. Litman (2008) suggested that factors that affect accessibility include transportation demand and activity, mobility, transportation options, user

information, integration, terminals and parking, affordability, mobility substitute, land use, transportation network connectivity, roadway design and management, prioritization, and the value of inaccessibility. More detailed descriptions of these factors are provided in Table A.9 in Appendix A.

It is clear from the descriptions of the accessibility factors that the easier to reach desired destinations, the better the accessibility. Hence, it can be deduced that accessibility is dependent on whether an area's transport service is convenient to most users or not, and it is mainly affected by transport network completeness and the required travel time for each transport service.

As the comparison of the alternative transit systems in this research is based on the same route and the same number of stations, it follows that these alternative systems have the same transport network. Furthermore, the travel time for each transit system has been considered earlier under 'performance'. Therefore, the accessibility attribute can be excluded from the evaluation analysis.

Mobility is the efficient movement of people. For transit systems, it can be defined as travel efficiency, which generally depends on headway and operating speed. These have been taken into consideration earlier in the "travel time" attribute. Hence, mobility will not be evaluated explicitly in this study.

Access Difficulty to the Disabled. The completeness of barrier-free facilities is usually used to compare convenience and accessibility to the disabled between transit systems. There are two main areas for provision of barrier-free facilities: station and vehicle. For stations, barrier-free facilities are to enable the disabled to

have convenient access to stations, movement within stations, as well as boarding at platforms. These include disabled ticket vending machine, disabled access gate, slop, elevator, platform design, route for the blind, station services for the disabled, etc. For vehicles, the barriers-free facilities refer to vehicle floor design, kneeling devices on vehicles for boarding/alighting, exclusive spaces for the disabled, etc.

In modern transit systems, accessibility to the disabled can be suitably considered if the system planners are conscious of this issue and the available budget allows. Therefore, medium-capacity transit systems can offer good accessibility to the disabled through the provision of adequate barrier-free facilities which is mainly a cost item. Since system costs are a major consideration in the evaluation of alternative transit systems, it is not necessary to evaluate this attribute separately.

Congestion is estimated as the additional trip time over that required under free flow conditions. Clearly, free-flow travel time before and after an alternative system is implemented should not change. Hence, the change in congestion is the difference in trip time with and without the alternative system. Given the better performance of medium-capacity transit systems, it is logical to expect congestion to decrease with the introduction of such a system. That is, the *congestion* attribute can be regarded as a benefit which can be evaluated by computing the reduction in trip time for all users (inclusive of passenger and commercial road users as well as transit passengers) after the alternative is implemented.

Trip time is calculated separately for the peak and off-peak periods. In the DSS, there are three ways to obtain trip time of each road transport mode:

- (1) The user can provide average trip time for both peak and off-peak periods if they have these information;
- (2) Alternatively, the user can provide average travel speed of each mode during the peak and off-peak periods, and trip time for each mode can be estimated by dividing average travel distance by speed;
- (3) Finally, the user can provide the v/c ratio, the relationship between volume (demand in passenger car equivalent) and capacity, for the peak and off-peak periods as well as the design speed (or speed limit) of the road so that the DSS can perform speed estimation. This speed estimation is based on an applicable speed-flow relationship and the flow and capacity inputs. In reality, it is difficult to obtain a speed-flow relationship for urban roads because of the effects of many factors such as intersection spacing, traffic signal phasing, green time, cycle time, etc. Here, as a crude approximation in the absence of appropriate user inputs, the speed flow relationship for two-lane (each direction) urban highways from the Highway Capacity Manual of Taiwan (HCMT) is used as a reference (see Figure 4.2), and the calculation procedure is as follows:
 - (i) When volume is higher than capacity (i.e., $v/c > 1$), traffic is in oversaturated conditions (levels of service E and F in Figure 4.2). In reality, oversaturated conditions are very unstable, and it is difficult to know what the speed is. Fortunately, such conditions do not happen regularly even in the peak hour. It is assumed in this study that v/c does not exceed unity and the speed-flow relationship can be represented as in Figure 4.3, which gives a capacity of 2050 pcu/hour/lane for a design speed of 80 km/h.

Figure 4.2 Speed-flow Relationship: Two-lane Urban Highway in Taiwan
(Source: Highway Capacity Manual in Taiwan)

Figure 4.3 Speed-flow Relationship of Two-lane Highway in Taiwan
(Undersaturated Conditions)

- (ii) The DSS asks the user to provide the design speed of the road and the v/c in the peak and off-peak periods of the study area.
- (iii) The speed for traffic in the study area for both the peak and off-peak periods can then be estimated by:

$$S_{s \frac{v}{c}} = \frac{DS_s}{DS_H} \times S_{H \frac{v}{c}} \quad (4.8)$$

where,

DS_s = the design speed of the road in the study area;

DS_H = the design speed from the HCMT (i.e. 80 km/hour);

$S_{H\frac{v}{c}}$ = the speed from the HCMT at the same (v/c) condition as the study area.

Since the speed information provided by HCMT is a speed-flow curve rather than a function, the DSS has built-in points from the curve (i.e., several speed values corresponding to selected v/c ratios – see Table 4.6). The $S_{H\frac{v}{c}}$ values for other v/c ratios can be found by interpolation.

Table 4.7 Speed v Volume/Capacity from the Curve in Figure 4.3

Flow	0	500	700	900	1100	1300	1500	1600	1800	2000	2050
Speed	80	78	77	76	74.5	72.5	70	68.5	65	59.5	55
v/c	0	$\frac{500}{2050}$	$\frac{700}{2050}$	$\frac{900}{2050}$	$\frac{1100}{2050}$	$\frac{1300}{2050}$	$\frac{1500}{2050}$	$\frac{1600}{2050}$	$\frac{1800}{2050}$	$\frac{2000}{2050}$	1

The calculation of *Congestion* in terms of Total Congestion Benefit for alternative i, or TC_i , is presented below.

$$TC_i = TTB - TTA_i \quad (4.9)$$

where,

TTB = Total travel time before implementing any transit alternative (hours/year),

TTA_i = Total travel time after implementing transit alternative i (hours/year).

Prior to the implementation of alternative i:

$$TTB = \sum_p TTB_p = \sum_p \sum_m NB_{pm} ATB_{pm} = \sum_p \sum_m NB_{pm} AD/ASB_{pm} \quad (4.10)$$

where,

TTB_p = Total travel time in period p (peak or off-peak) before implementing any transit alternative (hours/year),

NB_{pm} = Number of person trips in period p by mode m (passenger car, motorcycle, commercial vehicle, or existing transit system) before implementing any transit alternative (trips/year),

ATB_{pm} = Average trip time by mode m in period p before implementing any alternative (hours/trip),

ASB_{pm} = Average travel speed by mode m in period p before implementing any alternative (km/hour),

AD = Average trip distance for road transport (assumed to be the same for each type of road transport, with and without implementing the alternative system).

After implementing alternative i:

The operating speed of the alternative system is assumed to be the same in the peak and off-peak periods in this study. Therefore, the average travel times per passenger for the alternative system in the peak and off-peak periods are the same.

$$\begin{aligned} TTA_i &= TTA_{i_existed} + TTA_{ii} \\ &= \sum_p \sum_m NA_{ipm} ATA_{ipm} + NA_{ii} ATA_{ii} \\ &= \sum_p \sum_m NA_{ipm} AD/ASA_{ipm} + NA_{ii} ATA_{ii} \end{aligned} \quad (4.11)$$

where,

$TTA_{i_existed}$ = Total travel time by existing modes (including passenger car, motorcycle, commercial vehicle, and regular bus) after the implementation of alternative i (hours/year),

TTA_{ii} = Total travel time of passengers using alternative i after the implementation

of alternative i (hours/year),

NA_{ipm} = Number of person trips in period p by mode m (passenger cars, motorcycles, commercial vehicles, or existing transit system) after implementing transit alternative i (trips/year),

ATA_{ipm} = Average trip time by mode m in period p after implementing transit alternative i (hours/trip),

NA_{ii} = Number of trips using alternative i after it is implemented (persons/year),

ATA_{ii} = Average travel time of a trip using alternative i after it is implemented (hours/trip),

ASA_{ipm} = Average travel speed by mode m in period p after implementing alternative i (km/hour).

Note that in the above computation, a trip means an O-D person trip rather than a vehicle trip.

The value of time (VOT) is the ratio of the marginal utilities of time and money (Wardman, 2004). VOT is often used to convert time into a monetary unit in the evaluation of congestion cost. There are various opinions on this from past studies: Litman (2007) proposed that traffic congestion costs consist of incremental delay, driver stress, vehicle costs, crash risk and pollution resulting from interference between vehicles in the traffic stream, particularly as a roadway system approaches its capacity. Downs (1992) calculated the marginal delay caused by an additional vehicle entering the traffic stream by taking into account the speed-flow relationship of each road segment to obtain the congestion cost. The concept of traveler's

willingness-to-pay (WTP) has also been used to investigate the charges required to reduce demand to the design capacity. Another approach is to calculate the unit cost of current expenditure on congestion reduction projects (Litman, 2007).

The most common method for estimating VOT is to use the average wage rate in the service area of the transit system. In this study, the computation of VOT as used in the Highway Economic Requirements System (HERS) of the US Federal Highway Administration (FHWA) is followed. In this method, work trip travel time is valued at the average wage rate, and the value of non-work trip travel time is 45 percent of the average wage rate (FHWA, 2002). In this study, work trips are regarded as peak hour trips, and non-work trips are assumed to be off-peak trips. Hence, *Congestion* benefits of alternative i by VOT ($CVOT_i$) can be calculated:

$$CVOT_i = \sum_p VOT_p TTB_p - \sum_p VOT_p TTA_{ip} \quad (4.12)$$

where,

VOT_p = Value of time in period p . Note that $VOT_p = AW$ when p is in peak period, and $VOT_p = 0.45AW$ when p is in off-peak period.

AW = Average wage (\$/hour).

For this study, the default average wage is based on the 2008 wage data in Taiwan extracted from DGBAS (2009). Details are given in Table A.8 of Appendix A, The average monthly wage is NT\$ 45998.4 (US\$ 1367) and the average monthly work hour is 181.9 hours. These yield an average wage of US\$7.5 per hour.

VOT is mainly a concept to estimate the social cost/benefit of a project (usually transport facilities) and is often used by transport economists and planners in the

evaluation of economic feasibility of the project. Given the various methods of estimating VOT, and that it is a virtual cost rather than a real one, two options will be available to the user for evaluating congestion in the DSS developed in this study. One is to use congestion time directly, and the other is converting time into a monetary unit using VOT as given in Equations (4.13) and (4.14), respectively, where TC_i is the change in congestion time, and $CVOT_i$ is the congestion cost.

$$\text{Comparing Congestion Time} \quad TC_i = TTB - TTA_i \quad (4.13)$$

$$\text{Comparing Congestion Cost} \quad CVOT_i = \sum_p VOT_p TTB_p - \sum_p VOT_p TTA_{ip} \quad (4.14)$$

New Retail Floor-space. Transit system operation can bring business opportunities and generate new retail floor-space to areas adjacent to the transit lines. Although the alternative systems have the same routing and number of stations, the level of business opportunities created by each alternative system may differ (e.g. different grades of rail structures may lead to different levels of store visibilities). In general, it is difficult for planners/DSS users to estimate the level of increase in new retail floor-space. However, they may know the likelihood of an increase in business opportunities for each transit system. Hence, this attribute is treated as a binary dummy variable: if an alternative system has the potential to increase business opportunity, it is set equal to 1. Otherwise, it has a value of 0.

Safety. In the past, market prices (e.g., lost productivity, property damage, medical treatment, insurance administration, public agency overhead, prevention/protection expenditures) are usually used for estimating the cost of safety. These do not included all the costs of safety such as pain/suffering and traffic delay caused by

accidents which are not easy to value (Wang, 2008). In addition, market prices are typically derived from willingness-to-pay (WTP). Clearly, WTP would vary from city to city and from person to person, and is rather subjective. Furthermore, only very few countries (e.g. the US) have established their own WTP values. Most other countries then use the relationship between their own GDP or value of statistical life (VSL) and those of the U.S to develop their own WTP (Wang, 2008). This approach makes the resulting WTP not very credible. Therefore, safety is expressed in qualitative terms for comparing alternative transit systems in this study.

Safety of a transit system consists of two parts: system safety and passenger safety. Assuming that all transit systems considered are new and well-designed with no inherent system problems, then safety is only affected by factors related to other road users. The effects of these factors on system safety and passenger safety are discussed in the following paragraphs.

1. System Safety

This can be determined by the level of separation from other transport users: larger separations mean less interference and better safety. The right-of-way (ROW) categories can present the level of separation from other transport modes and users. If the transit line/network is fully separated (ROW A) from other transport modes, it should be very safe. If it is mixed with other traffic (ROW C), then it is not so safe. In the DSS, the safest case has a score of 10, and the most unsafe case has a score of 0. In this DSS, the safety scores for ROW A, ROW B and ROW C are 10, 5 and 0, respectively. Hence, for a transit line/network with segments belonging to several categories of ROW, the safety level is determined by the percentage of route length in each ROW category (see Figure 4.4). It is noted that other factors such as

population distribution and amounts of roadway users may also affect safety but are not considered in this study.

Figure 4.4 Determination of System Safety in the DSS

2. Passenger Safety

Passenger safety is mainly affected by access to the transit station/stop, in particular, whether passengers need to cross roads to access the station/stop. Passenger safety level also ranges from 0 to 10 in this DSS (see Figure 4.5). A value of 10 implies all stations of the transit network are either on the curbside or with underpasses or overhead bridges that passengers can access the station without having to cross roads, while a value of 0 means passengers need to cross roads to access any of the stations. Thus, if there are m stations in the network, and n of them can be reached without crossing the road, then the passenger safety level is given by $(n/m)*10$.

Figure 4.5 Determination of Passenger Safety in the DSS

4.1.2.3 Environmental Sustainability

Energy Consumption. Most cities are concerned about growing automobile dependency, and a critical factor is the energy problem (Kenworthy, 2003). Public transit is a major key to energy conservation because transit vehicles use less energy

than automobiles on a passenger-km basis (APTA website). Differences in energy use, occupancy, vehicle type, etc. affect the energy consumption of a transit system. Hence, it is important to compare energy consumption between alternative systems. Energy cost has been included as *power cost* under operating and maintenance costs of the *costs* attribute. In addition, the *CO₂ emission* and *air pollution* attributes also account for the environmental and health impacts of energy consumption. Clearly, this attribute should be excluded from the analysis to avoid double-counting.

CO₂ Emission. CO₂ is the leading greenhouse gas (GHG) which contributes to global warming and other environmental damages. Most climatologists believe that human activity is the main generator of CO₂ emission. Concerns about climate change have led to the signing of the Kyoto Protocol by more than 140 nations to commit to reductions in their GHG emissions. Increased use of public transit is often seen as a GHG reduction strategy. The USA transportation sector produced 27% of total GHG emissions in 2003, second only to the electricity generation sector (Vincent and Jerram, 2006). It is therefore important for planners to take CO₂ emission into consideration when planning for transport facilities. Consequently, CO₂ emission is one of the considerations in comparing transit systems in the DSS.

CO₂ is emitted from almost all transport-related events: not only from travel but also from construction and maintenance of transport facilities. For transportation, CO₂ emission can be regarded as a life cycle emission that happens all the time. However, life cycle emission is complex and difficult to estimate and it varies from area to area. Therefore, the DSS only takes into consideration CO₂ emission from travel, which includes emissions from driving of passenger cars, motorcycles,

existed transit systems (regular buses), and alternative systems. That is, it can be calculated from the fuel or electricity used during operation. The CO₂ emission data of various transport modes are given in Table A.10 to Table A.27 of Appendix A.

In this DSS, the reduction in CO₂ emission after the implementation of a transit system (RCO_{2i}) is used for comparing alternative transit systems. That is:

$$RCO_{2i} = TCO_2B - TCO_2A_i \quad (4.15)$$

where,

TCO_2B, TCO_2A_i = total CO₂ emission before and after implementing alternative i.

Since medium-capacity transit systems are for passengers, they do not affect commercial vehicles. Hence, one can ignore CO₂ emission from such vehicles. TCO_2B represents CO₂ emissions from passenger-carrying vehicles such as cars, motorcycles, and existing transit vehicles (usually regular buses) before alternative system i is implemented. TCO_2A_i represents CO₂ emissions from these vehicles as well as the emissions from alternative transit system i after its implementation.

The amount of vehicle CO₂ emission is affected by engine type, temperature, speed, etc. Detailed estimation of these through the entire planning period is impossible. It is assumed that CO₂ emission per km for each transport mode is only affected by travel speed. Similar to the computation of *congestion*, estimation of CO₂ emissions in the DSS is divided into two parts, peak and off-peak periods, as outlined below.

A. Estimate total CO₂ emission before implementing alternative system (TCO_2B).

- (1) Obtain annual vehicle-distance travelled in the study area by passenger cars, motorcycles, and the existing transit system for both peak and off-peak

period.

$$DB_{pm'} = AD \times nB_{pm'} = AD \times (nB_p \times \%B_{pm'}) = AD \times (NB_{pm'} / \alpha B_{pm'}) \quad (4.16)$$

$$\text{where } nB_p = \sum_{m'} nB_{pm'} = nB_p \times \left(\sum_{m'} \%B_{pm'} \right) = \sum_{m'} NB_{pm'} / \alpha B_{pm'} \quad (4.17)$$

$$\text{and } \sum_{m'} \%B_{pm'} = 1$$

$DB_{pm'}$ = total annual vehicle distances traveled in period p (peak or off-peak) by mode m' (passenger cars, motorcycles or existing transit system) before implementing alternative system,

nB_p = annual number of passenger transport vehicles in period p before implementing alternative system,

$nB_{pm'}$ = annual number of mode m' in period p before implementing alternative system,

$\%B_{pm'}$ = percentage of mode m' in period p before implementing alternative system,

$\alpha B_{pm'}$ = occupancies of mode m' in period p before implementing alternative system,

(2) Compute total annual CO₂ emissions from those of each transport mode.

$$TCO_2 B_{m'} = \sum_p DB_{pm'} ACO_2 B_{pm'} \quad (4.18)$$

$$TCO_2 B = \sum_{m'} TCO_2 B_{m'} \quad (4.19)$$

where,

$TCO_2 B$ = total annual CO₂ emission before implementing alternative transit system,

$TCO_2 B_{m'}$ = total annual CO₂ emission from mode m' before implementing alternative transit system,

$ACO_2 B_{pm'}$ = CO₂ emission per vehicle-km from mode m' in its average

speed in period p.

Table 4.8 Default Values of CO₂ Emission for Road Vehicles (NETCEN, 2003)

$EF(g \text{ CO}_2/\text{km}) = (a + b*v + c*v^2 + d*v^e + f*\ln(v) + g*v^3 + h/v + i/v^2 + j/v^3)*x,$ v is speed in kph												
Vehicle Type	Reference	a	b	c	d	e	f	g	h	i	j	x
Passenger Car	Euro II	37.25	-0.096	0.00072	0	0	0	1.23E-05	602.314	5.871	0	3.14
Motorcycle	Pre-2000	79.378	-2.299	0.031255	0	0	0	-0.00013	0	0	0	3.14
Bus	Euro II	200.3	2.93E-04	-0.0156	0	0	0	1.75E-04	26.0	29113	-111672	3.14

Table 4.9 Default Occupancies for Passenger Road Vehicles

Vehicle Type	Occupancy (passengers/vehicle) ()
Passenger Vehicle	$P_C = 1.75$ (Taiwan)
Motorcycle	$M = 1.13$ (Taiwan)
Original Transit System (Regular Bus)	$T = 19$ (Taiwan); 9 (USA)

B. Estimate total CO₂ emission with alternative transit system i, TCO_2A_i .

(1) Compute total annual CO₂ emission of alternative system i, TCO_2A_{ii}

$$TCO_2A_{ii} = \frac{TOT_i}{AH_i} \times L_i \times CO_2A_i \quad (4.20)$$

where TOT_i = Total operating time per year for alternative i (min),

AH_i = Average headway for alternative i (min/TU),

L_i = total length of the alternative line/network (km),

CO_2A_i = CO₂ emission of the alternative per TU-km.

Table 4.10 Default CO₂ Emission Rates for Various Transit Systems

Type	Energy Type	CO ₂ Emission (kg/TU-km)
Standard BRT & Guided Bus	Diesel	0.866
	CNG	0.682
	LPG	0.852
	Electricity	1.146
Articulated BRT & Guided Bus	Diesel	1.368
	Electricity	1.328
Bi-Articulated BRT & Guided Bus	Diesel	1.258
LRT & LRRT	Electricity	1.478

(2) Evaluate CO₂ emission of passenger transport except alternative i, or ($\sum_{m'} TCO_2 A_{im'}$, where mode m' is passenger car, motorcycle, or existing transit system). Here, $TCO_2 A_{im'}$ is the total CO₂ emission by mode m' after alternative i is implemented. It was mentioned earlier that total overall O-D trips by passengers is unchanged after the implementation of alternative i. That is,

$$\begin{aligned}
 NB = NA_i &\Rightarrow \sum_{m'} NB_{m'} = \sum_{m'} NA_{im'} + NA_{ii} \\
 &\Rightarrow \sum_p \sum_{m'} NB_{pm'} = \sum_p \sum_{m'} NA_{ipm'} + NA_{ii}
 \end{aligned} \tag{4.21}$$

where,

NB, NA_i = total amount of O-D trips before and after an alternative system i is implemented (person-trips/year);

$NB_{m'}, NA_{im'}$ = the amount of O-D trips by mode m' before and after alternative i is implemented (person-trips/year);

The sum of $NB_{pm'}$ is the total amount of O-D trips before implementing an alternative. The quantity $\sum_{m'} NA_{im'}$ can be obtained if NA_{ii} can be estimated for each alternative system i. Note that if the user has the O-D trip matrix which

shows $NA_i \neq NB$, the DSS will allow the user to input either NA_i or each $NA_{ipm'}$.

To calculate the annual volumes of passenger cars, motorcycles, and existing transit vehicles in both the peak and off-peak periods after implementing alternative i (i.e., $nA_{ipm'}$, where p is peak or off-peak hour, m' is passenger car, motorcycles, or existing transit vehicle), the user needs to provide the percentages of these vehicles in the traffic mix as well as their respective occupancies after the implementation of alternative i . These volumes are then multiplied by the average trip distance (AD) and the amounts of CO₂ emissions of each mode to compute the annual CO₂ emissions after alternative i is implemented. The calculation process is presented in the following:

$$DA_{ipm'} = AD \times nA_{ipm'} = AD \times (nA_{ip} \times \%A_{ipm'}) = AD \times (NA_{ipm'} / \alpha A_{ipm'}) \quad (4.22)$$

$$TCO_2 A_{im'} = \sum_p DA_{ipm'} \times ACO_2 A_{ipm'} \quad (4.23)$$

where,

$$\sum_{m'} \%A_{ipm'} = 1; \quad p = \text{peak or off-peak period}$$

$DA_{ipm'}$ = total annual vehicle distances traveled by mode m' in period p after implementing alternative i ,

nA_{ip} = annual number of passenger transport vehicles in period p after implementing alternative i ,

$nA_{ipm'}$ = annual number of mode m' in period p after implementing alternative i ,

$\%A_{ipm'}$ = percentage of mode m' in period p after implementing alternative i ,

$\alpha A_{ipm'}$ = occupancies of mode m' in period p after implementing alternative i,

$TCO_2 A_{im'}$ = total annual CO₂ emission from mode m' after implementing alternative i,

$ACO_2 A_{ipm'}$ = CO₂ emission per vehicle-km from mode m' in its average speed in period p after the implementation of alternative i.

C. Determine the reduction in CO₂ emission after implementing alternative i.

$$RCO_{2i} = TCO_2 B - TCO_2 A_i = TCO_2 B - (TCO_2 A_{ii} + \sum_{m'} TCO_2 A_{im'}) \quad (4.24)$$

In many applications, a monetary unit is often used for evaluating CO₂ emissions. There are two major costs of CO₂ emission: one is external costs which represents the costs of environmental and health damages caused by CO₂ emission; and the other is carbon trading costs. The latter emanates from the Kyoto Protocol which specifies a carbon quota for each signatory nation to the Protocol. If a nation generates more CO₂ than its quota, it can buy quota from another nation. This is known as carbon trading. Since the external costs of CO₂ are notional that do not involve real money, and are defined differently in different studies, the DSS in this study will confine the CO₂ emission cost to the carbon trading costs only.

There are several carbon trading systems in the world, and the European Union Emission Trading Scheme (EU ETS) is the biggest one and the European Climate Exchange (ECX) is the main trading market of EU ETS. In this study, the CO₂ trading cost is based on data from ECX, and the default value is set at the average front settlement prices from the start of 2009 to 16 April 2009, which is €11.40 per ton of CO₂. Given that the CO₂ trading price varies from day to day (see Figure

A.2), the user can refer to the ECX website (ECX, 2009) to update the CO₂ trading price.

In summary, the user can choose one of two ways to evaluate the CO₂ emission attribute: (1) by the amount of CO₂ emission (tons/year) calculated from Eq. (4.24); or (2) by carbon trading, which is computed by multiplying the carbon trading price by the annual CO₂ reduction after implementing an alternative transit system.

Air Pollution. CO₂ emissions are generally relevant on a global scale. To evaluate the environmental effects caused by transit modes on a localized level which can directly influence the health of people, air pollution is a proper attribute.

As with CO₂ emission, the reduction in air pollutant emissions after implementing an alternative transit system is used for evaluating the air pollution attribute in the DSS. However, air pollution includes several pollutants and there are various standards for estimating air pollution. For example, the USA Federal Clean Air Act indicates six main air pollutants: carbon monoxide (CO), nitrogen dioxide (NO₂), ozone (O₃), particulate matter (PM), lead (Pb), and sulfur dioxide (SO₂) (Hensher and Button 2003), while the Hong Kong Air Pollution Index does not take Pb into consideration. The major pollutants from roadway vehicles are hydrocarbons (HC), CO, and oxides of nitrogen (NO_x), while SO_x is the main pollutant from electricity generation by coal which is a major method of generating electricity in the world today, and transit systems such as LRT are propelled by electricity.

There are also several methods for evaluating air pollution. Some use the weights of pollutants (e.g. the MOBILE model). Some consider air pollutant concentrations

and indexes are used to compare pollution levels (e.g. API). Still others convert the pollutant emissions to different amounts of unit cost, depending on its damage to human and aggregate the costs of all pollutants for comparing alternative systems.

To estimate the reduction in air pollution, the type of pollutants and measurement unit should be the same for all transport modes. Furthermore, the amount of air pollutant emissions is affected by factors such as local temperature, vehicle speeds, and trip distances. Therefore, it is rather difficult to achieve realistic estimations.

A study by Delucchi (2006) provides CO, NO_x, SO_x, PM, N₂O, NMHC, NMOG, CH₄, C₆H₆, HCHO, CH₂CHCHCH₂, CH₃CHO, and CH₂CH₂ emissions (in g/kWh) for each type of electricity generation. It also gives emission estimates for buses and automobiles (in g/mile) based on a reference trip in Sacramento which is at a speed of 55 miles/hour (88.5 km/hour). Delucchi's air pollutant estimates for the various transport modes in the speed of 55 mph are converted into total air pollutants in g/km and summarized in Table 4.10(a) and Table 4.10(b) (details can be found in Appendix A, Tables A.28, A.33 to A.36). These are used as the default values in the DSS.

Table 4.11 (a) Air Pollutant Emitted by Passenger Road Transport

(Source: Delucchi, 2006, the data in Sacramento)

	Type	Energy Type	Air Pollutant (g/km)
Passenger Road Transport	Passenger Vehicle	Petrol	5.0628
	Motorcycle	Petrol	-
	Regular Bus	Diesel	39.3849

Table 4.11 (b) Air Pollutant Emitted by Medium-Capacity Transit System

(Source: Delucchi, 2006)

	Type		Energy Type	Air Pollutant (g/km)
Medium-Capacity Transit System	BRT & Guided Bus by Fuel		Diesel	25.584
			Natural Gas (CNG)	18.627
			LPG	18.804
	Guided Bus by Electric	Standard	Electricity	1.709
		Articulated	Electricity	1.980
	LRT & LRRT		Electricity	2.204

As with the calculation of congestion and CO₂ emissions, the amounts of air pollution are also calculated separately for peak and off-peak periods, by taking into consideration the difference in “speed” between peak and off-peak periods. There is a lack of information in NETCEN (2003) on the relationship between speed and pollutant emission for some of the air pollutants. Therefore, the data in Table 4.10 (a) and the relationship between energy consumption and speed from NETCEN (2003) are used together to estimate the relationship between speed and pollutant emission for these pollutants. As mentioned earlier, Delucchi’s (2006) data on air pollution by automobiles is for a speed of 55 miles/hour (88.5 km/hour). Using the speed-energy consumption factors of the road transport modes in Table 4.11, the amounts of pollutants for each mode at various speeds can be calculated by:

$$AP_x = AP_{88.514} \times (EC_x / EC_{88.514})$$

where,

AP_x (g/km) = amount of air pollution at x kph;

$AP_{88.5}(\text{g/km})$ = amount of air pollution at 88.5 kph (known) (passenger car: 5.0628; bus: 39.3849);

$EC_x(\text{g/km})$ = amount of energy consumptions at x kph (known);

$EC_{88.514}(\text{g/km})$ = amount of energy consumptions at 88.5 kph (known) (passenger car: 49.706; bus: 203.218).

Table 4.12 Modal Speed-Energy Consumption Factors (NETCEN, 2003)

EF(g fuel/km) = (a + b*v + c*v^2 + d*v^e + f*ln(v) + g*v^3 + h/v + i/v^2 + j/v^3)*x, v is speed in kph												
Vehicle Type	Reference	a	b	c	d	e	f	g	h	i	j	x
Passenger Car	Euro II	37.247	-0.096	0.00072	0	0	0	1.23E-05	602.314	5.871	0	1
Motorcycle	Pre-2000	79.378	-2.299	0.031	0	0	0	-0.00013	0	0	0	1
Bus	Euro II	200.3	2.93E-04	-0.0156	0	0	0	1.75E-04	26.0	29113	-111672	1

Note that there is no information on the amount of air pollutants emitted by a motorcycle. The values in Table 4.10(a), was estimated based on the relationship of fuel consumption efficiency. That is, air pollution amount of a motorcycle is:

$$AP_x = AP_{88.514} \times (EC_x / EC_{88.514}) = 5.0628 \times (EC_x / 49.706)$$

where AP_x = amount of air pollution emitted by a motorcycle at x kph;

EC_x = amount of energy consumption of motorcycle at x kph (known).

The amount of air pollutants from a transit mode using electric-power is based on its electricity consumption rate. For example, LRT consumes an average of 2.56 kWh/km, a standard guided bus using electricity consumes 1.985 kWh/km on average, and an articulated guided bus uses an average of 2.3 kWh/km (see Table A.36). The amount of air pollutants (see Table A.10 (b)) is obtained through multiplying the electricity consumption by a default air pollutant emission rate of

0.861 g/kWh (the average of several areas in the USA as presented in Table A.35).

The procedure for calculating air pollutants is described in the following:

A. Estimate total air pollutant amounts before implementing alternative i (TAPB).

- (1) Calculate total annual air pollutants by adding together the annual air pollutants emitted by each mode.

$$TAPB = \sum_{m'} TAPB_{m'} \quad (4.25)$$

where,

$$TAPB_{m'} = \sum_p (DB_{pm'} \times AAPB_{pm'}) \quad (4.26)$$

TAPB = Annual total air pollution before implementing alternative system,

$TAPB_{m'}$ = Annual total air pollution by mode m' before implementing alternative transit system,

$AAPB_{pm'}$ = air pollution per vehicle-km from mode m' in its average speed in period p .

B. Estimate total air pollutant amount with alternative transit system i ($TAPA_i$).

- (1) The total annual air pollutant amount for alternative system i ($TAPA_{ii}$).

$$TAPA_{ii} = \frac{TOT_i}{AH_i} \times L_i \times APA_i \quad (4.27)$$

where APA_i = air pollutant amount of alternative i per TU-km (g/TU-km).

The default values for APA_i (in g/TU-km) in the DSS are as follows: BRT and Guided Bus: 25.584 (diesel), 18.627 (CNG), 18.804 (LPG), 1.709 (standard electric), 1.980 (articulated electric); LRT and LRRT = 2.204.

(2) The air pollution of passenger transport (excluding alternative system i)

($\sum_{m'} \text{TAPA}_{im'}$) is:

$$\sum_{m'} \text{TAPA}_{im'} = \sum_{m'} \left(\sum_p \text{DA}_{ipm'} \times \text{AAPA}_{ipm'} \right) \quad (4.28)$$

where,

$\text{TAPA}_{im'}$ = total annual air pollutant amount from mode m' after implementing alternative i ,

$\text{AAPA}_{ipm'}$ = air pollutant amount per vehicle-km from mode m' in its average speed in period p after the implementation of alternative i ,

C. Finally, air pollution reduction after the implementing alternative i , (RAP_i) is:

$$\text{RAP}_i = \text{TAPB} - \text{TAPA}_i = \text{TAPB} - (\text{TAPA}_{ii} + \sum_{m'} \text{TAPA}_{im'}) \quad (4.29)$$

For the same reasons mentioned earlier in the discussion on CO₂ emissions, external costs are also not considered in evaluating air pollution. Unlike CO₂ emissions, air pollutant emissions have no agreed quota, so they do not have ‘trading costs’. Hence, the evaluation of air pollution for the alternative transit systems is confined to a comparison of reductions in air pollutant emissions (in g/km) due to the implementation of each the alternative systems.

Noise. There are several single-number descriptors for transit-noise measurement and assessment. These include: *A-weighted Sound Level* which describes the noise at an instant; *Maximum Sound Level* (L_{max}) is the noise during a single noise event; the *Sound Exposure Level* (SEL) gives the cumulative noise exposure from a single

noise event; the *Hourly Equivalent Sound Level* ($L_{eq}(h)$) describes the cumulative noise exposure from all events over a one-hour period; and the *Day-Night Average Sound Level* (L_{dn}) describes cumulative noise exposure from all events over a 24-hour period, with events between 10 pm and 7 am increased by 10 decibels to account for greater nighttime sensitivity to noise (FTA, 2006).

Among these, L_{dn} is the most realistic noise descriptor, but its calculation is rather complicated as it considers a large number of factors such as vehicle speed, hourly traffic volume, ambient sound level, time for crossing signals, noise of yards, shops and stations, noise barriers, etc. The DSS uses as default values the SEL of each system (in dBA, see Table A.33) from the USA Federal Transit Administration (FTA, 2006) for comparing noise between alternative systems. If noise impact of the systems is a concern, then the user should commission a separate noise study. And if an alternative system has both at-grade and elevated segments, then the noise level of alternative system i in the line/network ($Noise_i$) can be estimated by Eq. (4.30). Once the noise levels of all alternatives have been estimated, the noise attribute for the alternative systems can be compared quantitatively.

$$Noise_i = \sum_a (Noise_a \times a_i\%), \quad (4.30)$$

where a = the transit mode with a given alignment,

$Noise_a$ = the noise level of 'a',

$a_i\%$ = percentage of the length of 'a' in the line/network of alternative i .

4.1.3 Summary of Transit System Attributes

From the discussion on the preliminary attributes, a set of 12 attributes are selected for comparing alternative systems. Of these, five can be converted to monetary unit.

Table 4.10 summarizes this final set of attributes and the evaluation method to be used for each attribute in the development of the DSS.

Table 4.13 Final Selected Attributes and Evaluation Method

Categories	Attribute	Technical Feasibility	Comparison of alternatives	Unit of Measure
Performance	Line capacity	✓	✓	one-way space/hr
	Reliability		✓	qualitative
	Curvature	✓		meters
	Gradient	✓		%
	Travel time (system efficiency)		✓	min/trip
Economic	Costs		✓	\$/yr
Sustainability	Revenues		✓	\$/yr
Social Sustainability	Congestion		✓	\$/yr or passenger-hr/yr
	Increased business opportunity		✓	dummy variable
	System Safety		✓	qualitative
	Passenger Safety		✓	qualitative
Environmental Sustainability	CO ₂ emission		✓	\$/yr or tons/yr
	Air pollution		✓	tons/yr
	Noise		✓	dBA

4.2 Study Methodology

The study approach and methodology are discussed based on the flow chart of the associated Decision Support System (DSS) which is presented in Figure 4.4.

First, technical feasibility is analyzed to determine whether all alternative systems are suitable/feasible for the planned basic transit line/network. This involves two aspects: geographical constraints and system demand. Geographical constraints are those imposed by site terrain and alignment of the planned lines/networks. The

minimum radius of the horizontal curve and maximum gradient are two major factors in determining geographical feasibility. Consideration of system demand is to ascertain that the line capacity of an alternative system can meet the expected passenger demand of the proposed line/network. A transit system is technically feasible if it demonstrates both geographical and system demand feasibility.

If all alternative transit systems are technically feasible, then one can proceed to evaluate the alternative systems. Otherwise, the user needs to decide whether to revise the planned line/network so that more alternative systems can be technically feasible, or exclude the unfeasible alternative system(s) from further consideration.

The DSS has three major subsystems: a knowledge subsystem, a language subsystem, and a problem-processing subsystem. The knowledge subsystem releases the requests of the DSS, the language subsystem presents the requests to the user, and the problem-processing subsystem delivers these requests to, and accepts the replies from, the user. The DSS is an interactive system that enables communication with the user. A series of processes is used in this methodology and the DSS to obtain the attribute measures for each transit alternative from the user.

Figure 4.4 Flow Chart for Transit Systems Evaluation Methodology

A classical approach is used to combine all attributes into a single score. Weights are to be assigned to the system attributes to reflect the relative importance of each attribute. As discussed in Chapter two, a review of the literature has concluded that the objective method of assigning weights by the entropy concept is thought to be inappropriate for this analysis. Hence, the assignment of weights to the attributes in this study will be subjective in nature -- based on the user's opinion regarding the relative importance of each attribute for the specific city concerned. The next step of the proposed methodology is to integrate all system attributes and take them into consideration simultaneously when comparing and evaluating the alternative systems. As discussed earlier, several past studies used Multi-Attribute Evaluation (MAE) methodologies to integrate system attributes. A number of MAE methodologies are available, and the selection of a particular MAE method depends on the form of the attribute measure (e.g. quantitative values or qualitative levels).

In this study, some system attributes are measured by quantitative values while others are expressed in qualitative levels. It was mentioned in Chapter 2 that the Multicriteria Evaluation with Qualitative and Quantitative Data (MEQQD) method is often used for evaluation in such cases. MEQQD establishes dominance levels by using normalization which considers only the relativities between alternatives for the same attribute. This is a weakness because the same dominance level for different attributes does not have the same meaning, so MEQQD is not suitable for comparing alternatives with attributes which have different measurement units. To address this problem, an improved MEQQD needs to be developed for comparing alternative systems. The idea is to convert as many quantitative attribute measures as possible into a unified unit. *Cost* has been the most commonly used basis for

comparing transit systems in many studies because it is familiar to decision-makers and easy to understand. Hence, the approach in this study is to convert quantitative attributes to a monetary unit if possible, and the remaining attributes will still be compared using the conventional MEQQD. In other words, the monetary measure is combined with the conventional MEQQD to form an improved MEQQD for evaluating alternative systems by comparing several attributes simultaneously. In addition, a financial analysis is also carried out to provide information concerning the financial feasibility of each alternative system to the user. The process of this approach is briefly outlined below:

1. Classify all system attributes into three groups: (a) those that can be converted into monetary units, (b) those that cannot be converted into monetary units but are measured quantitatively, and (3) attributes that can only be expressed in term of qualitative levels.
2. The improved MEQQD described above is applied to convert each group of attributes to the same basis of measurement, and then integrate all three groups of attributes into an index for each alternative system considered.
3. A financial analysis using the *costs* attributes is carried out to present the financial feasibility of each alternative transit system.

With the index values produced by the improved MEQQD as well as the results of the financial analysis for all the alternative systems studied, a user will have the necessary information to make a decision regarding the most appropriate transit system for the planned basic line/network.

It should be noted that the best transit system for the planned basic line/network does not necessary mean that it is the most suitable solution for the study area. There might be another line/network configuration that is more appropriate than the planned one. Therefore, the DSS will remind the user to try other feasible transit lines/networks. By testing different lines/networks with the DSS, several best transit alternatives for different lines/networks can be obtained. The most appropriate transit system for the study area is then determined through a comparison of the best alternative transit system for each of the lines/networks investigated.

CHAPTER 5 DEVELOPMENT OF THE DECISION SUPPORT SYSTEM

The Decision Support System (DSS), as the name implies, is a “supporter” rather than a “decision maker”. In this study, it is designed to assist the user in finding an appropriate transit system for the study area. It is an interactive system that allows the DSS to obtain relevant information from the user and, in turn, provides the user with analysis and evaluation results about alternative transit systems, as well as suggestions to assist the user in the selection of a suitable transit system.

In this study, five alternatives are available for consideration and evaluation in the selection of a suitable transit system. These include the ‘do-nothing’ alternative and four medium-capacity transit systems: BRT, guided bus, LRT, and LRRT/AGT. The characteristics of these transit systems are shown in Table 5.1. The user has the option to add other medium-capacity transit systems as alternative systems. Note that the “Do-nothing” alternative is always one of the alternatives for comparison.

Table 5.1 Characteristics of Medium-Capacity Transit Systems

Transit System	Steered / Guided	Vehicle	Vehicle Power	ROW Category	ROW Type
BRT	Steered	Bus	Diesel/ CNG/ LPG/ Electric	B or C	At-grade
Guided bus	Guided	Bus	Diesel/Electric	A	Elevated/at-grade
LRT	Guided	LRV	Electric	B or C	At-grade
LRRT	Guided	LRV	Electric	A	Elevated

As discussed in Chapter 4, twelve system attributes are included in the DSS for the

evaluation of alternative systems. Some attributes are quantitative while others are qualitative. An important task in this study is to integrate all attributes into a single index for comparing the alternatives. The MEQQD is a method that can evaluate both quantitative and qualitative attributes simultaneously (Voogd, 1982; Feng, 1988). The DSS in this study uses an improved MEQQD method. We shall first briefly describe the MEQQD method here.

5.1 The MEQQD Method

The procedure in the application of the MEQQD method can be generalized and presented as shown in Figure 5.1.

Figure 5.1 The MEQQD Method

First, the qualitative and quantitative attributes are categorized into two sets. Set C contains all quantitative attributes, and Set O contains all qualitative attributes. The

measures of all quantitative attributes are then normalized as in Eq. (5.1).

$$\bar{e} = (e_{ij} - e_{i,\text{worst}}) / (e_{i,\text{best}} - e_{i,\text{worst}}) \quad (5.1)$$

where $\bar{e}$ = the normalized value of e_{ij} ,

e_{ij} = the value of attribute i for alternative j ,

$e_{i,\text{best}}, e_{i,\text{worst}}$ = best and worst values for attribute i among all alternatives.

Next, the dominance levels of the alternative systems are determined. This is done for both the qualitative and quantitative attributes. The MEQQD method determines the dominance level of qualitative attributes as the F Function in Eq. (5.2):

$$\begin{aligned} a_{jj'} &= F(e_{ij}, e_{ij'}, W_i), i \in O \\ &= \sum_i [W_i(e_{ij} - e_{ij'})] \end{aligned} \quad (5.2)$$

where $a_{jj'}$ = the difference in the measured levels of qualitative attributes between alternative j and alternative j' ;

W_i = the weight assigned to qualitative attribute i .

e_{ij} and $e_{ij'}$ are the measured levels of attribute i for alternatives j and j' . To determine e_{ij} and $e_{ij'}$ for a qualitative attribute, the standards of measure for all qualitative attributes i are first set to the same. For example, the ranges of measurement level for all such attributes are all set to between 0 and 10. Then, based on questionnaire survey or expert opinions, the level of attribute i for each alternative are determined within this range.

Similarly, the MEQQD method determines the dominance level of quantitative attributes as the G Function in Eq. (5.3):

$$\begin{aligned}
c_{jj'} &= G(\overline{e_{ij}}, \overline{e_{ij'}}, W_i), i \in C \\
&= \sum_i [W_i^* (\overline{e_{ij}} - \overline{e_{ij'}})]
\end{aligned} \tag{5.3}$$

where $c_{jj'}$ = the difference in the measured levels of quantitative attributes between alternative j and alternative j' ,

W_i^* = the weight assigned to quantitative attribute i .

The dominance levels are then normalized. There are two basic assumptions in MEQQD: one is that the mean appraisal score of each alternative is a constant (assumed to be 0); the other is that the dominance level of alternative j to alternative j' is the difference of these two appraisal scores. Mathematically, if there are J alternatives, these basic assumptions are expressed as:

$$\frac{1}{J} \sum_j s_j = 0 \quad \text{where } s_j \text{ is the appraisal scores of alternative } j \tag{5.4}$$

$$m_{jj'} = K(s_j, s_{j'}) = s_j - s_{j'} \tag{5.5}$$

$$\text{Now, define } m_{jj'} = W_O b_{jj'} + W_C d_{jj'} \tag{5.6}$$

$$\text{where } W_O = \sum_{i \in O} W_i, \quad W_C = \sum_{i \in C} W_i \tag{5.7}$$

$$\text{and } W_O + W_C = 1 \tag{5.8}$$

Let $b_{jj'}$ and $d_{jj'}$ be the normalization of the dominance level of qualitative and quantitative attributes for alternative j compared to alternative j' . With

$$b_{jj'} = H(a_{jj'}) = \frac{a_{jj'}}{\sum_j \sum_{j'} |a_{jj'}|} \tag{5.9}$$

$$d_{jj'} = H(c_{jj'}) = \frac{c_{jj'}}{\sum_j \sum_{j'} |c_{jj'}|} \tag{5.10}$$

Now, calculate the appraisal score of each alternative. From Eq. (5.5), $m_{jj'} = s_j - s_{j'}$

so

$$\sum_{j'} m_{jj'} = \sum_{j'} s_j - \sum_{j'} s_{j'} = Js_j - \sum_{j'} s_{j'} \quad (5.11)$$

After rearranging terms, one obtains

$$s_j = \frac{1}{J} \sum_{j'} m_{jj'} + \frac{1}{J} \sum_{j'} s_{j'} \quad (5.12)$$

Given that $\frac{1}{J} \sum_{j'} s_{j'} = 0$ [Eq. (5.4)],

$$\text{It follows that } s_j = \frac{1}{J} \sum_{j'} m_{jj'} \quad (5.13)$$

The process of normalization for quantitative attributes in MEQQD is used to address the issue of different units between attributes. However, the same score for different attributes after normalization does not have the same meaning because the normalization is based on the relativities between alternatives for the same attribute. Therefore, the score of the best alternative for any attribute is always 1 and the score of the worst alternative for any attribute is always 0. Hence, an improved methodology needs to be developed to solve or minimize this problem in the DSS.

5.2 Development of the DSS

The methodology of the DSS is elaborated using a more detailed flow chart than that presented in Chapter 4 (see Figure 5.2). The entire process of the DSS development is divided into several subdivisions which include Parts A to E and Decisions A, B and C. The development of the DSS will be elaborated subdivision by subdivision in Sections 5.2.1 to 5.2.7.

Figure 5.2 Framework and Subdivisions of the DSS Development

5.2.1 Technical Feasibility (Part A)

A basic transit line/network should first be planned as the reference basis for the comparison of alternative transit systems. This line/network can be planned in one of two ways depending on whether the planner has a basic transit system in mind. In most cases, planners have a transit system in mind first and then plan a line/network to meet the demand of the planning area. This transit system on which planning is based is called the 'basic system' in this study.

In such a case, the user would only have the projected demand for the basic system and not those of the alternative transit systems. Consequently, if a user wants to compare the basic system with other transit systems, the demand levels of the other transit systems can only be assumed to be the same as the 'basic system' - this is one way of comparison. In practice, different transit systems may attract different levels of passenger demand. Therefore, if a user has done the planning study based on the alternative transit systems, then the demand levels of these alternative systems can be used - this is the other way of comparison.

Another reason for allowing these two ways of comparison is that when the basic line/network is planned for a basic system, and the evaluation results showed that this basic system is not the best alternative, then line/network re-planning should be performed. This is because other transit line/network configuration may be more appropriate for that best alternative. On the other hand, if the basic line/network is planned without a basic system in mind, the best alternative from the evaluation can then be regarded as the best for this line/network configuration.

Before evaluating the alternative systems to choose a suitable system for the study area, the DSS needs to have information about the basic line/network and technical data associated with the alternatives from the user. In addition, the DSS needs to first ascertain that each alternative is technically feasible for the planned basic line/network. This involves evaluating geographical and system demand feasibility.

Geographical constraints are imposed by terrain and the alignment of lines/networks within the study area. Minimum radius and maximum gradient are two main factors to consider in assessing geographical feasibility. Information on the required minimum radii and maximum gradients for the alternative systems and the design values for the basic line/network should be provided to the DSS. If the planned minimum radius and maximum gradient of the basic line/network meet the required values for an alternative system, then geographical feasibility is achieved.

System demand feasibility is assessed to ensure that the capacity provided by an alternative can satisfy the expected demand. System demand is often represented by the Design Hourly Volume (P_{max}), which is the 30th highest one-way hourly passenger demand of the year among all section of the line. For a transit system, P_{max} may be affected by trip distribution, attractiveness of the transit system such as comfort, safety, and efficiency, etc. Hence, even though the basic line/network is the same, different transit systems may have different P_{max} . The capacity of a transit system is represented by *line capacity* (C) which is the number of spaces that a transit system can provide per hour [Eq. (5.14)]. An alternative has system demand feasibility if its line capacity exceeds the expected demand (i.e., $C \geq P_{max}$).

$$C = f_{\max} \cdot n \cdot C_v = (60 / H_{\min}) \cdot C_{TU} \quad (5.14)$$

where,

$f_{\max}$ = maximum frequency (TUs/hour-direction),

$H_{\min}$ = minimum headway (minutes/TU),

C_v = vehicle capacity (spaces/vehicle),

n = vehicles per TU,

C_{TU} = TU capacity (spaces/TU).

In the above, $H_{\min}$ is also called safe headway, and the decision on $H_{\min}$ or $f_{\max}$ for a transit system is dependent on the desired safety level for that system.

With information on the basic line/network and the alternative transit systems, the technical feasibility of each alternative can be ascertained if: (a) the minimum radius of the alternative is not larger than that of the basic line/network; (b) the maximum gradient of the alternative is not smaller than that of the basic line/network; and (c) the line capacity of the alternative is not smaller than the system demand.

The logic and procedure of Part A (Technical Feasibility) are summarized in the flow chart shown in Figure 5.3.

Figure 5.3 Tests of the Technical Feasibility for Alternative Systems

5.2.2 Confirmation of Technical Feasibility for All Alternatives (Decision A)

As discussed, each alternative system has earlier been tested for technical feasibility. The objective of this subdivision is to make sure that all alternative systems are technically feasible in relation to the basic line/network. That is, all the alternative systems can be constructed and operated on the basic line/network. If one or more alternatives are found to be unfeasible, the DSS will inform and ask the user to make one of two decisions: (a) to revise the basic line/network (or re-plan a

line/network), or (b) to eliminate unfeasible alternative system(s) from further evaluation. The flow chart of this subdivision is shown in Figure 5.4.

Figure 5.4 Confirmation of Technical Feasibility for All Alternative Systems

5.2.3 Process of Collecting Attribute Measure (Part B)

The definitions of system attributes selected for evaluating alternative systems were discussed in Chapter 4. These are reproduced here as Table 5.2 for easy reference. Information on attribute measures is to be provided by the user to the DSS before the comparison of alternative systems. The amount of available data on alternative systems may differ from user to user. Some may have a complete set of data, others may only have attribute measures of alternative systems, and yet others may have only a few components of attribute measure. Therefore, the DSS should guide and assist the user in the collection of attribute measures of alternative systems.

Table 5.2 Definitions of Attribute Measures

Category	Attributes	Definitions
Performance	Line capacity	Number of spaces per hour per direction at a point on the transit line at minimum headway
	Reliability	(qualitative)
	Travel Time (System Efficiency)	minutes per trip
Economic Sustainability	Costs	Total costs in base year value divided by design life of system (\$/year)
	Revenues	Total revenues in base year value divided by design life of system (\$/year)
	CO ₂ emission (carbon trading) ^a	Total CO ₂ emission reduction/year by passenger trips multiply by carbon trading price (\$/year)
	Congestion ^b	Total travel time savings per year multiply by VOT (\$/year)
Social Sustainability	Congestion ^b	Total travel time savings (passenger-hour /year)
	Increased business opportunities	Dummy variable (0 or 1)
	System Safety	Depend on percentage of ROW (qualitative)
	Passenger Safety	Depends on whether passengers need to cross road to access transit station/stop (qualitative)
Environmental Sustainability	CO ₂ emission ^a	Total CO ₂ emission reduction per year by passenger trips (tons/year)
	Air pollution	Total air pollution reduction per year by passenger trips (tons/year)
	Noise	Depends on the percentage of length of each type of alignment and mode (dBA)
<p>Note:</p> <p>a. Evaluation of CO₂ emission depends on whether carbon trading is practiced. If yes, CO₂ emission is treated as an economic attribute. Otherwise, it is an environmental attribute.</p> <p>b. Evaluation of congestion depends on whether time saving should be valued as benefits in a monetary unit using VOT. Thus, <i>congestion</i> is either a social sustainability attribute or an economic sustainability one.</p>		

In collecting attribute measures, the DSS asks the user to provide information on the measures of an attribute for each alternative. If the user needs clarification about an attribute, he can ask the DSS for a more detailed description. The DSS would then ask the user for other data to obtain information on that attribute measure. Figure 5.5 illustrates an example of collecting information on the *Costs* attribute measures.

A similar process is repeated for each of the attributes until all the required data have been collected.

Figure 5.5 Procedure for Collecting “Costs” Attribute Measures

The user may express the *Congestion* attribute in hours/year or \$/year. Similarly, the user may express the *CO₂ emission* attribute in tons/year or \$/year. If these attributes are expressed in \$/year, they are grouped under *Economic Sustainability* rather than under *Social Sustainability* or *Environmental Sustainability*. Note that, for evaluation purpose, each attribute can only be in one of the categories.

As discussed earlier, the MEQQD method has a weakness that the process of normalizing quantitative attributes may cause problem. To mitigate this potential problem, this study aims to combine the units of as many quantitative attributes as possible into the same type. That is, if the attributes are expressed in the same unit, they do not need to be normalized in order to be integrated with other attributes.

In past studies, a monetary unit (for costs, revenues, and other economic benefits) is the most often used measure for transit system evaluation. Most quantitative attributes in this study are expressed in *dollars per year*. Therefore, it is logical to use it as a unified unit. This means there are three categories of attributes: the ones that are expressed in a monetary unit (\$/year), those measured in quantitative terms, and those described in a qualitative form. In this DSS, the *Costs*, *Revenues*, *CO₂ emission*, and *Congestion* attributes are measured in \$/year. It is clear that *Costs* and *Revenues* are in this unit. The *CO₂ emission* and *Congestion* attributes can either be in this unit or in other quantitative forms depending on the choice of the user.

The attributes expressed in \$/year can be divided into real money or virtual money. For example, construction costs are real money, whereas congestion cost converted with value-of-time (VOT) is virtual money. Since a dollar in virtual money may not be the same as a dollar in real money to the user, the DSS asks the user to give the equivalence between virtual money and real money. Then a new attribute is created to replace these monetary attributes by integrating all of these attributes as follows:

$$e_{Mj} = \left(\sum_{i \in M, i \in \text{real_money}} e_{ij} \right) + \frac{1}{V} \left(\sum_{i \in M, i \in \text{virtual_money}} e_{ij} \right) \quad (5.15)$$

where e_{Mj} = measure of new monetary attribute of alternative j ,

V = equivalent dollars of virtual money to \$1 of real money,

M = {the set of all attributes which are expressed in \$/year}.

The DSS adds up values of all attributes in the unified unit (\$/year) into a new attribute, and then combines it with the MEQQD method to form an improved MEQQD method for evaluating alternative transit systems. The procedure (Part B) is summarized in Figure 5.6.

Figure 5.6 Procedure for Collecting Attribute Measures

Note that some attribute measures for the “Do-nothing” alternative have values of 0, as there is no difference between the ‘with’ and ‘without’ alternative case, These include *congestion*, *business opportunity increase*, *CO₂ emission*, and *air pollution*.

5.2.4 Assign Attribute Weights (Part C)

It is clear that the importance of each of the attributes would vary from one user (area) to another. In additions, the users of the DSS are planners who are professional in transit systems and familiar in the study areas. Hence, the weighting

(representing the importance) of each attribute is best set by the user (called the subjective way in this study). If users do not know about the importance of the attributes, they can consult experts (eg. Do expert questionnaire) to get information. These will then be taken into account in combining the attributes for evaluation of alternative systems.

In some past studies, for example Feng (2004) and Hwang and Yoon (1981), a hierarchical weighting method was used in an hierarchical framework. The method guides the user step by step in deciding weights. This hierarchical weighting method is briefly described below.

(1) Develop a hierarchical relationship. A study has a goal which has a few objectives, and each objective has several attributes. The alternatives are evaluated by these attributes. Relationships between the goal, objectives and attributes can be built by a hierarchical framework such as that shown in Figure 5.7. In this Figure, W_1 and W_2 are the weights of the two objectives O_1 and O_2 under the goal G . The weights w_{11} and w_{12} are for attributes A_1 and A_2 under objective O_1 ; and w_{23} , w_{24} and w_{25} are the weights for attributes A_3 , A_4 , and A_5 under the objective O_2 .

Figure 5.7 Example of a Hierarchical Framework

(2) Establish the pair-wise comparison matrix. The example in Figure 5.7 can be divided into three pair-wise comparison units (see Figure 5.8). The component weights in a unit should add up to 1. The pair-wise comparison matrix is developed by comparing component to component in the unit.

Figure 5.8 Example of Pair-wise Comparison Units

For example, Unit 3 in Figure 5.8 has three components A₃, A₄, and A₅. Its pair-wise comparison matrix (A) is as shown in Figure 5.9, in which a_{ij} represents the ratio of the weight for component i (w_i) to the weight for component j (w_j).

Figure 5.9 Example of a Pair-wise Comparison Matrix

In theory, the following relationships should be satisfied:

$$a_{ij} = w_i / w_j \quad (5.16)$$

$$a_{ik} = a_{ij} \times a_{jk} \quad (5.17)$$

$$a_{ij} \times a_{ji} = 1 \quad (5.18)$$

$$a_{ii} = 1 \quad (5.19)$$

In this study, the a_{ij} values in the pair-wise comparison matrix are obtained through direct input from the user. Past studies have often employed intensity scales of importance (see Table 5.3) to indicate the relative importance between components in a pair-wise comparison unit. Using Figure 5.10(a) as an example, the pair-wise comparison matrix shown in Figure 5.10(b) can be constructed.

Table 5.3 Intensity scale of importance for attributes

Intensity of importance	Definition	Explanation
1	Equal importance	Both criteria contribute equally to the objective.
3	Weak importance of one over another	Experience and judgment slightly favor one criterion over another.
5	Essential or strong importance	Experience and judgment strongly favor one criterion over another.
7	Demonstrated importance	A criterion is strongly favored and its dominance is demonstrated in practice.
9	Absolute importance	The evidence favoring one criterion over another is of the highest possible order of affirmation.
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed between adjacent judgments.

	9	8	...	3	2	1	1/2	1/3	...	1/8	1/9	
Component 1								✓				Component 2
Component 1				✓								Component 3
Component 2	✓											Component 3

(a)

$$A = \begin{bmatrix} 1 & 1/3 & 3 \\ 3 & 1 & 9 \\ 1/3 & 1/9 & 1 \end{bmatrix}$$

(b)

Figure 5.10 Example of the Construction of a Pair-wise Comparison Matrix

(3) Calculate the weights of components in each pair-wise comparison unit. Two main methods can be used to calculate weights from a pair-wise comparison. One is the *Eigenvector Method* and the other is the *Weighted Least-Squares Method*. The former was introduced by Saaty (1977). It involves scaling ratios using the principle

eigenvector of a positive pair-wise comparison matrix. The latter was proposed by Chu et al. (1979) which uses optimization and Lagrangian function to obtain the weight solution from a set of linear algebraic equations. In this study, the *Weighted Least-Squares Method* is preferred because it is conceptually easier to understand than the *Eigenvector Method*, it. The following briefly describes this method.

Weighted Least-Squares Method: given the elements a_{ij} of the comparison matrix A ,

We wish to determine the weights (w_i). From Eq. (5.16), $a_{ij} = w_i / w_j$. The weights can be obtained by solving the constrained optimization problem:

$$\min \quad z = \sum_{i=1}^n \sum_{j=1}^n (a_{ij} w_j - w_i)^2 \quad (5.20)$$

$$\text{s.t.} \quad \sum_{i=1}^n w_i = 1 \quad (5.21)$$

In order to minimize z , the Lagrangian function Eq. (5.22) is employed in which λ is the Lagrangian multiplier. Differentiating Eq. (5.22) with respect to w_ℓ , the set of equations [Eq. (5.23)] is obtained.

$$L = \sum_{i=1}^n \sum_{j=1}^n (a_{ij} w_j - w_i)^2 + 2\lambda \left(\sum_{i=1}^n w_i - 1 \right) \quad (5.22)$$

$$\sum_{i=1}^n (a_{i\ell} w_\ell - w_i) a_{i\ell} - \sum_{j=1}^n (a_{\ell j} w_j - w_\ell) + \lambda = 0, \quad \ell = 1, 2, \dots, n \quad (5.23)$$

Eq. (5.21) and Eq. (5.23) form a set of $(n+1)$ non-homogeneous linear equations with $(n+1)$ unknowns, which include the weights of each attribute ($w_i, i = 1, 2, \dots, n$) and λ . Hence, these unknowns can be solved.

(4) Calculate the weights of system attributes. After obtaining the weights of the

components of all pair-wise comparison units in the hierarchical framework, the weight of a system attribute can be calculated by multiplying the weight of an objective (criterion) by the attribute weight under that objective. In Figure 5.7, the weight (w_4) of attribute A_4 can be calculated by multiplying the weight (W_2) of objective O_2 and the weight (w_{24}) of attribute A_4 under objective O_2 .

The goal of this DSS is to choose an appropriate alternative transit system. Four criteria (objectives): *Performance*, *Economic Sustainability*, *Social Sustainability*, and *Environmental Sustainability* are used to achieve this goal. Several system attributes are used in the DSS under these criteria. A hierarchical framework (see Figure 5.11) is used to obtain the importance of these criteria and attributes from the user's point of view. It offers the user more detailed information and meaning of each attribute so as to assist the user in providing their inputs to the DSS. The flow chart in Figure 5.12 summarizes the approach for assigning weights in this study. The results of attribute categorization in the DSS are shown in Figure 5.13.

Figure 5.11 Hierarchical Framework of Attributes in the DSS

Figure 5.12 Approach to Assign Attribute Weights in the DSS

Figure 5.13 Categorization of Attributes in the DSS

5.2.5 Combining Attributes for Alternative Comparison (Part E)

The evaluation of medium-capacity transit systems comprises two parts. One is to assess whether it is financially feasible to construct the alternatives. The other is to integrate all the system attributes into a single index for comparing alternative systems. From the DSS outputs, the user can review the results of all the alternative systems and select the best alternative for the planned transit line/network. These two parts of the evaluation are described in the following.

1. Financial Comparison. Finance is a very important factor in the selection of a transit system. In general, the financial concern is the cost involved in building a transit system because it reflects the funds required to develop the system. That is, the user can gauge from the construction cost whether the available budget can cover the cost of the alternative system.

As discussed earlier, *costs* comprise investment costs, operation and maintenance (O&M) costs, and vehicle/equipment replacement costs. With the data on *costs* for each alternative system (see Section 5.2.3), the costs of the alternative systems from this comparison are presented in “total costs” rather than “average annual costs” so that the user is informed of the total expenditure needed for each alternative system.

2. Integrating All System Attributes. The aim of this study is to develop a methodology that enables the planner to compare and evaluate alternative transit systems by considering all relevant system attributes simultaneously. This is achieved through an improved MEQQD method developed in this study. The method integrates all the system attributes into a single index for each alternative

system which can then be used for evaluating alternative transit systems.

The improved MEQQD is basically similar to the original MEQQD method. The difference is, in addition to categorizing the system attributes into two separate sets O and C , respectively, of qualitative and quantitative attributes; the former also includes a new attribute M created by combining all the attributes that are measured in \$/year. After this categorization of system attributes, Eq. (5.1) is used to compute the normalized value, $\bar{e}$, of each quantitative attribute i for alternative j or e_{ij} .

Next, the dominance levels of qualitative ($a_{jj'}$) and quantitative ($c_{jj'}$) attributes are determined using, respectively, the F and G functions of Eq. (5.2) and Eq. (5.3). The improved MEQQD also determines the dominance level ($p_{jj'}$) of the new attribute M as the H Function in Eq. (5.24):

$$p_{jj'} = (e_{Mj} - e_{Mj'}) \quad (5.24)$$

where $p_{jj'}$ = the difference in the measured levels of the new attribute M between alternative j and alternative j' ,
 e_{Mj} = from Eq. (5.15).

The computed dominance levels are then normalized. For the new attribute M , the normalized dominance level ($q_{jj'}$) for alternative j compared to alternative j' is:

$$q_{jj'} = H(p_{jj'}) = \frac{p_{jj'}}{\sum_j \sum_{j'} |p_{jj'}|} \quad (5.25)$$

The normalized dominance levels of qualitative ($b_{jj'}$) and quantitative ($d_{jj'}$) attributes for alternative j compared to alternative j' are as calculated from Eq. (5.9) and Eq. (5.10), respectively. These are reproduced below for reference.

$$b_{jj'} = H(a_{jj'}) = \frac{a_{jj'}}{\sum_j \sum_{j'} |a_{jj'}|}$$

$$d_{jj'} = H(c_{jj'}) = \frac{c_{jj'}}{\sum_j \sum_{j'} |c_{jj'}|}$$

Define

$$m_{jj'} = W_O b_{jj'} + W_C d_{jj'} + W_M q_{jj'} \quad (5.26)$$

$$\text{where } W_O = \sum_{i \in O} W_i; W_C = \sum_{i \in C} W_i; W_M = \sum_{i \in M} W_i. \quad (5.27)$$

$$\text{and } W_O + W_C + W_M = 1 \quad (5.28)$$

Now calculate the appraisal score (s_j) of each of the J alternatives. This calculation basically follows the original MEQQD method presented earlier in Eq. (5.12) and Eq. (5.13), and are reproduced below. The process of the improved MEQQD is also summarized in Table 5.4 and Figure 5.14.

$$s_j = \frac{1}{J} \sum_{j'} m_{jj'} + \frac{1}{J} \sum_{j'} s_{j'}$$

$$\text{or } s_j = \frac{1}{J} \sum_{j'} m_{jj'}, \quad \text{since } \frac{1}{J} \sum_{j'} s_{j'} = 0 \quad [\text{from Eq. (5.4)}].$$

Table 5.4 Categories and Symbols Used in Improved MEQQD Method

Attribute, i		Weighting, W_i	Attribute Measures for Alternatives, $e_{ij}(\bar{e}_{ij})$
			Alternative, $j \quad j = 1, 2, \dots$
$i \in C$	$i = 1, 2, \dots$	$\sum W_i = 1$	$e_{ij}(\bar{e}_{ij})$
$i \in O$			
$i \in M$

Figure 5.14 Procedure of the Improved MEQQD Methodology

5.2.6 The Best Alternative for the Basic Line/Network (Decision B)

The user will be able to choose the best transit alternative for this basic planned line/network by referring to the results on finances and evaluation index for each

alternative system. When the basic transit line/network is planned with a particular transit system (called the *basic alternative* in this study) in mind, it is possible that the best system selected through the evaluation process is not this *basic alternative*. In such a case, there may be other configurations for the transit line/network which are more suitable for the selected system than the basic line/network.

Therefore, the DSS in this subdivision would first check whether the basic transit line/network is planned with a *basic alternative* in mind. If the answer is affirmative, then the DSS would check whether this *basic alternative* is the best alternative selected by the evaluation process. If this is not the case, a re-planning of the basic line/network should be performed with the selected best system in mind to determine whether there are more suitable transit line/network configurations for this selected system (see flow chart in Figure 5.15).

Figure 5.15 Flow Chart for the Subdivision of Decision B

5.2.7 Consideration of Other Line/Network Configuration (Decision C)

As mentioned above, the best alternative for the planned basic transit line/network may not necessarily be the most appropriate solution for the study area. Through an examination of other line/network configurations, the user may find that some other configuration could be more appropriate than the original planned one. In this subdivision, the DSS reminds the user to investigate other transit line/network configurations to find out whether there are better solutions. Figure 5.16 presents the flow chart of this subdivision.

Figure 5.16 Flow Chart for the Subdivision of Decision C

For each line/network configuration, the DSS produces the best alternative system for that configuration, using the same weights of attributes provided. By applying different line/network configurations repeatedly, there will be several best transit system alternatives, one for each line/network configuration studied. The optimal transit system for the study area is one that is the best among the selected alternative

systems for all the line/network configurations considered.

With the same methodology used in Part E, the user would be able to choose this optimal transit system by comparing the financial results and indexes for these best alternatives. Note that since the calculation of the indexes for the alternatives is based on the relative values of the attribute measures between the compared alternatives, the index for each alternative will change as the transit line/network configuration changes.

5.3 Summary

The DSS in this study is developed to assist and support the user in the selection of a suitable medium-capacity transit system for a study area. The DSS consists of three interacting components: a language system, a knowledge system, and a problem-processing system. For example, the actions of asking the user to input the required information of alternatives and the weights of attributes belonged to the language system; the calculation of weights and integration of attributes are part of the knowledge system; and the components for connecting the information from the language system and the calculation processes of the knowledge system are part of the problem-processing system.

An interface is needed for this DSS to facilitate interaction between the user and the language system of the DSS. In the next Chapter, an interface will be built. In addition, the application of this DSS will be demonstrated with an example of the selection of a medium-capacity transit system for the Tamsui area in Taiwan.

CHAPTER 6 APPLICATION OF THE DECISION SUPPORT SYSTEM

In this chapter, an easy-to-use interface is built for application of the DSS. By following the instructions in the interface, the user is guided in selecting an optimal medium-capacity transit system for the study area. In addition, the extension line of the Damsui rapid transit system in Taiwan is used as a demonstration of the DSS.

There are three sections in this Chapter. First, the development of the DSS interface is introduced. This is followed by a brief description of the extension line of Taiwan's Damsui rapid transit system which is to be used as a demonstration data. Finally, the DSS interface demonstration using the Damsui data is presented.

6.1 Development of the DSS Interface

The DSS interface is developed using the C# language in Microsoft Visual Studio 2008. The mainly reasons that C# language is selected for programming are: (1) it is an object-oriented language; (2) It belongs to the .NET Framework, so it can cross to other languages (a component can be created in one language and extended to another language); (3) it can also be used with other operating systems (e.g. Linux); and, (4) Microsoft Visual C# is easy-to-use for developing interfaces.

To develop the DSS interface for supporting users in finding an optimal medium-capacity transit system, the first step is the "window design" which is the language system of a DSS (see Section 2.5). It is aimed at designing windows to guide the user to input required data and to display instructions and results. After

that, the default data and the calculation and evaluation processes are coded in C# language. This creates the knowledge system of the DSS (see Section 2.5). Finally, a link is developed to enable the user and the DSS to communicate interactively. This is the problem-processing system of a DSS. With these steps, the interactive interface of the DSS assists the user in an easy-to-use manner.

6.2 The Extension Line of Damsui Rapid Transit System

To develop the Dan-Hai New Town, an extension line of the Damsui rapid transit system is planned. From the “Feasibility Study of the Extension Line of Damsui Rapid Transit System” report, the numbers of person trips in the planning area with and without a medium-capacity transit system in 2031 are estimated (Table 6.2.1).

Table 6.2.1 Amounts of Trips without Alternative Systems (Persons/Year)

Trips	Total trips (N^B)	Automobile ($N^B_{pc} + N_c$)	Motorcycle (N^B_m)	Regular bus (N^B_t)
Persons/yr	246,784,165	88,151,150	50,738,650	107,894,365

A combination of a line and a medium-capacity transit system is to be selected from among five alternative lines and two alternative systems. The five lines are: (1) Green Mountain Line, (2) Blue Ocean Line – Old Street, (3) Blue Ocean Line – Tai 2 Line, (4) Whole Line, and (5) Battery Park Line. The two systems are LRT (LRRT) and guided bus. As the DSS can also evaluate other systems such as BRT and AGT, the user can decide which alternative systems to include for study.

Green Mountain Line. The alignment and location of this line can be shown as Figure 6.2.1-(a), and the line information can be presented in Table 6.2.2-(a).

Figure 6.2.1-(a) Alignment and Location of Green Mountain Line

Table 6.2.2-(a) Green Mountain Line Information

Line Length (twice if two way)	19.368 km		
ROW Category (%)	A	B	C
	52.15	47.85	0
ROW Type (%)	At-grade		Elevated
	47.85		52.15
Station Crossing (double if two way)	No cross		Cross
	8		8
Minimum Radius	40 m		
Maximum Gradient	3.50%		

Blue Ocean Line – Old Street (A). The alignment and location of this line are shown in Figure 6.2.1-(b), and the line information is presented in Table 6.2.2-(b).

Figure 6.2.1-(b) Alignment and Location of Blue Ocean Line (A)

Table 6.2.2-(b) Blue Ocean Line (A) Line Information

Line Length (twice if two way)	16.38 km		
ROW Category (%)	A	B	C
	3.66	87.82	8.52
ROW Type (%)	At-grade		Elevated
	96.34		3.66
Station Crossing (double if two way)	No cross		Cross
	5		15
Minimum Radius	35 m		
Maximum Gradient	3.70%		

Blue Ocean Line – Tai 2 Line (B). The alignment and location of this line are shown in Figure 6.2.1-(c), and the line information is presented in Table 6.2.2-(c).

Figure 6.2.1-(c) Alignment and Location of Blue Ocean Line (B)

Table 6.2.2-(c) Line Information of Blue Ocean Line (B)

Line Length (twice if two way)	16.418 km		
ROW Category (%)	A	B	C
	30.76	69.24	0
ROW Type (%)	At-grade		Elevated
	69.24		30.76
Station Crossing (double if two way)	No cross		Cross
	12		8
Minimum Radius	35 m		
Maximum Gradient	3.70%		

Whole Line. The alignment and location of this line are shown in Figure 6.2.1-(d), and the line information are presented in Table 6.2.2-(d).

Figure 6.2.1-(d) Alignment and Location of Whole Line

Table 6.2.2-(d) Whole Line Information

Line Length (twice if two way)	25.88 km		
ROW Category (%)	A	B	C
	39.03	55.58	5.39
ROW Type (%)	At-grade		Elevated
	60.97		39.03
Station Crossing (double if two way)	No cross		Cross
	11		15
Minimum Radius	35 m		
Maximum Gradient	3.70%		

Battery Park Line. The alignment and location of this line are shown in Figure 6.2.1-(e), and the line information are presented in Table 6.2.2-(e).

Figure 6.2.1-(e) Alignment and Location of Battery Park Line

Table 6.2.2-(e) Line Information of Battery Park Line

Line Length (twice if two way)	14.19 km		
ROW Category (%)	A	B	C
	62.44	37.56	0
ROW Type (%)	At-grade		Elevated
	37.56		62.44
Station Crossing (double if two way)	No cross		Cross
	12		6
Minimum Radius	60 m		
Maximum Gradient	5%		

As can be seen, all five alternative lines have at-grade and elevated segments due to the terrain in this study area. In addition, space constraints make it not feasible to have ROW A for the at-grade segments. Hence, a fully-automated system cannot be provided in this area. As for possible transit systems, four alternatives can be evaluated in this DSS: (1) ‘do-nothing’, (2) LRT (LRRT), (3) BRT, and (4) guided bus. Data for *LRT (LRRT)* and *guided bus* are obtainable from the report, and the information of ‘do-nothing’ and *BRT* will be assumed by referring to default values or experiences of other areas. In addition, except for the ‘do-nothing’ alternative, the alignments of all alternative systems for the same line are the same. The data for each alternative system and each line are presented in Appendix B.

6.3 Application of DSS Using the Damsui Data

After completing the development of the DSS and obtaining the Damsui data, the application of the DSS is demonstrated using the Damsui data. Figure 6.3.1 shows how the interface looks like. The user should follow the guidance and instructions of the interface to input the data steps by steps, such as that shown in Figure 6.3.2.

Figure 6.3.1 Appearance of the DSS Interface

The screenshot shows the data input interface of the DSS. The window title is 'A Decision Support System for the Choice of Medium-Capacity Transit System'. The main text asks: 'Before using medium-capacity transit systems, what is the amount of annual trips of each existed mode in the study area?'. There are two buttons: 'Information is by Vehicle Number' and 'Information is by Road User Number'. Below these, there are two columns of input fields. The left column is for 'Peak Hours' and the right column is for 'Off-Peak Hours'. The first row is for 'Amounts of total trips counted by road user number: (Automobile + Motorcycle + Regular bus)'. The second row is for 'Distribution by road user number: Automobile : Motorcycle : Regular bus'. The third row is for 'Occupancies of modes (road users/vehicle):'. Below this, there are three rows of input fields for 'Automobile', 'Motorcycle', and 'Regular bus'. The fourth row is for 'Average travel distance: ... km/trip'. At the bottom, there are two questions: '1. Does the area implement carbon trading?' and '2. Do you think congestion is a kind of costs?'. Each question has 'Yes' and 'No' options with associated input fields. A red 'Next' button is at the bottom right.

Figure 6.3.2 Appearance of the DSS Interface for Data Input Process

To start, the amount of annual trips of each existing transport mode in the case of ‘without any medium-capacity transit system’ and the related data for both peak and off-peak periods are needed. The data can be entered in two ways depending on whether information is by vehicle volume or information is by road user volume. Table 6.3.1 shows the data needed.

Table 6.3.1 Information of the Trip Volumes without an Alternative System

Information by Vehicle Volume (peak and off-peak periods):	
Total trips counted by vehicle volume	vehicles/year
Distribution by vehicle volume (automobile : motorcycle : regular bus)	ratio
Occupancies of modes (including automobile, motorcycle, and regular bus)	passengers/vehicle
Information by Road User Volume (peak and off-peak periods):	
Total trips counted by road user volume	road users/year
Distribution by road user volume (automobile : motorcycle : regular bus)	ratio
Occupancies of modes (including automobile, motorcycle, and regular bus)	passengers/vehicle

Next, average travel distance of existing transport modes and whether CO₂ emission and congestion are treated as costs are to be specified by the user. In addition, average travel times per trip or average speeds for the peak and off-peak periods are required. For this case, average speeds are available (see Figure 6.3.3).

4 Decision Support System for the Choice of Medium Capacity Transit System

Do you know the average amount of **Speed** in the study area in **peak hours** and **off-peak hours** ?

Average Speed in Peak Hours

Car and Motorcycle: 13 kph

Regular Bus: 8 kph

Average Speed in Off-Peak Hours

Car and Motorcycle: 40 kph

Regular Bus: 16.54 kph

Figure 6.3.3 Appearance of the DSS Interface for Speed Input

After that, the basic line name, the situation whether the basic line is designed by a basic alternative, and the name of alternative transit systems are need to be entered.

With the above data, the first basic line and its alternative systems are confirmed. The DSS then asks for the characteristics of each alternative transit system and the information of the basic line. The data needed are shown in Table 6.3.2. If the user does not have some of these data, the interface provides some *default values* which the user may use (see example in Figure 6.3.4).

Table 6.3.2 Characteristic of Alternatives and Information of the Basic Line

Characteristics of Alternative Transit Systems	Information of the Basic Line
Vehicle type, power source, percentage of each ROW category (A, B, and C), percentage of ROW type (at-grade and elevated), station crossing, operating speed, TU capacity, technical minimum headway, minimum radius, and maximum gradient.	<p>Topographical Information: minimum radius of the line, maximum gradient of the line, and line length.</p> <p>Demand of alternative systems for the Line: peak hour demand, total annual demand, and average travel distance.</p>

The screenshot shows a software window titled "A Decision Support System for the Choice of Medium-Capacity Transit System". The main text says "Please input the alternative systems which will be compared in this basic line." Below this, there are several input fields and buttons. A red circle highlights a table of default values for operating speed and technical minimum headway. The table has columns for "Vehicle", "Power", "ROW Category", "ROW Type", and "Station crossing". The rows are "Do nothing", "Diesel", "CNG", "LPG", "BRT", "LRT (LRT/ST)", and "Gated Bus". The "Operating speed" column shows values like 15-25, 20-40, and 20-45. The "Technical Min. Headway" column shows values like 8-13, 15-40, and 15-40. The "Station crossing" column has checkboxes for "can be arrived w/o crossing" and "be arrived by crossing road". There are also buttons for "Default Values", "Full-Access", "Add", and "Exit".

Vehicle	Power	ROW Category	ROW Type	Station crossing
Do nothing				
Diesel		A	At-grade	can be arrived w/o crossing
CNG		B	Elevated	be arrived by crossing road
LPG		C		
BRT				
LRT (LRT/ST)				
Gated Bus				

Figure 6.3.4 Example of the DSS Providing Default Values

With the data provided by the user, the DSS performs technical feasibility analyses of the alternative transit systems. Figure 6.3.5 shows an example of the analysis results. If all the alternative systems analyzed are technically feasible, the “Next” button will appear. However, if one or more systems are technically unfeasible, the DSS will ask the user whether he wants to revise the line or remove the unfeasible alternative(s). For the Green Mountain Line of Damsui, all alternative systems are technically feasible, so the user can go on to the next stage.

The screenshot displays the 'A Decision Support System for the Choice of Medium-Capacity Transit System' interface. The main window is titled 'Please input the information of the basic line.' and contains two input sections: 'Geographical Information' and 'Demand'. The 'Geographical Information' section includes fields for 'Min. Radius' (40 meter), 'Max. Gradient' (3.5 %), and 'Line length' (19.368 km). The 'Demand' section includes fields for 'Peak Hour Demand' (Design Hourly Volume (Pmax)) and 'Annual Total Demand' (passengers/year), with a sub-section for 'Average riding distance' (km/passenger). Below these sections, a list of alternatives is shown, including 'Graded bus 1', 'Graded bus 2', 'Graded bus 3', 'Graded bus 4', and 'BRT'. A red box highlights the 'The Results of Technical Feasibility are:' section, which lists the results for each alternative, showing 'Do nothing', 'Capacity', 'Min. Radius', and 'Max. Gradient' for each. At the bottom, there are three buttons: 'Revise line', 'Eliminate unfeasible alternative(s)', and 'Next'.

Figure 6.3.5 Results of Technical Feasibility Shown in the DSS Interface

The next step is to input information for the peak and off-peak periods for the case ‘with’ the availability of an alternative transit system in the study area. The required data are total trip volume, distribution of modes, occupancies, and average speed data. In addition, the DSS also ask for information to calculate attribute measures for each alternative system. The interface is shown in Figure 6.3.6.

Figure 6.3.6 Interface for Input Information to Calculate Attribute Measures

If the user does not have the required data or does not understand the meaning of a request, he can click the “ ” button near the textbox to get more detailed information. If the user has no idea about congestion, he can click the “ ” button to ask the DSS to assist in the calculation. Table 6.3.3 lists the required data for the DSS, and Table 6.3.4 gives more detailed information on the required data.

Table 6.3.3 Data Required for the Calculation of Attribute Measures

Required Data	Unit
Total costs in base year value	\$
Annual revenues in base year value	\$/year
Average Headway	minutes/TU
Operating period	year
Reliability	qualitative level
Congestion	\$/year, hours/year
Potential of increased business opportunity	Yes or no (1 or 0)
Total annual operating time	hours/year

Table 6.3.4 More Detailed Information on the Required Data

Required Data	More Detailed Information		
Total costs in base year value	Investment costs	Planning and design	ROW acquisition
		Land acquisition	Station space acquisition
	O&M costs	Direct construction	Permanent way construction
		Indirect construction	Track superstructure
Annual revenues in base year value	Other Revenues	Contingencies	Station construction
			Construction for power supply
	Fare Revenues		Control and communication construction
			Maintenance and storage facilities
Annual revenues in base year value	Other Revenues		Vehicle acquisition
	Fare Revenues	Power	
		Vehicle operations	
Annual revenues in base year value	Other Revenues	Vehicle and Permanent-way maintenance	
		General and administration	
	Fare Revenues		
Annual revenues in base year value	Other Revenues		
	Fare Revenues		

After the required data have been entered, the user's opinions of the value of virtual money and the relative importance of the objectives and attributes are needed. By shifting the tracks shown in Figures 6.3.7 (a) and (b), the relative importance of the objectives and attributes can be specified and the attribute weights can be calculated.

Figure 6.3.7 (a) Decision for Relative Importance of Objectives

Figure 6.3.7 (b) Decision for Relative Importance of Attributes

Once data for the basic line, alternative systems, and the relative importance of objectives and attributes have been entered, the evaluation of the alternative systems is performed, and the results will be displayed to the user (see Figure 6.3.8).

Figure 6.3.8 Evaluation of Alternative Systems for Green Mountain Line

The results displayed in Figure 6.3.8 include the *Finance (Cost) Rank* (the lower the better), which is the total costs of the alternative systems; and the *Index (Score) Rank* (the larger the better), which integrates all 12 system attributes considered.

The planner (i.e., the DSS user) would have knowledge concerning the budget available for the provision of a medium capacity transit system for his/her area. So, the planner should first refer to the *Finance (Cost) Rank* which shows the cost of the system. If it is more than the available budget, then that particular transit system is not feasible and would not be considered further. For those transit systems that are within the available budget, the selection of the best alternative system then depends on the “*Index (Score) Rank*”. In other words, the best alternative transit system for a line is the one that has the best *Index (Score) Rank* and within the available budget.

In the case of Damsui, the available budget is assumed as 20 billions. Take the *Green Mountain Line* for example, which is shown in Figure 6.3.8, all transit systems are within the available budget except LRT. Guided bus 4 can be regarded as the best system for the line which is in the highest *Index Rank* from those alternative systems within the available budget.

The DSS then asks whether the user would like to study another line. In the case of Damsui, the above process would be repeated five times as there are five basic lines to be evaluated. Table 6.3.5 shows results of this evaluation for each basic line.

Table 6.3.5 Evaluation of Alternative Transit Systems for each Basic Line

	Alternative System	Finance (Cost) Rank	Index (Score) Rank
Green Mountain Line	Do-nothing	3340825800	-0.0289052718743993
	LRT	21778232000	0.0483780845255671
	Guided bus 1	11802487000	-0.00505989666114638
	Guided bus 2	11802487000	-0.00464886135054408
	Guided bus 3	11802487000	-0.0049081374280091
	Guided bus 4	11802487000	0.0020676526664056
	BRT	11802487000	-0.00686268247810879
Blue Ocean Line – Old Street	Do-nothing	3042355900	-0.0472860481606566
	LRT	17971226000	0.026409344268373
	Guided bus 1	8018561000	0.00355784825626515
	Guided bus 2	8018561000	0.00395226605445654
	Guided bus 3	8018561000	0.00370650691739596
	Guided bus 4	8018561000	0.0119598925607629
	BRT	8018561000	-0.00229980989659694
Blue Ocean Line – Tai 2 Line	Do-nothing	3062941000	-0.0465510351991097
	LRT	19524734000	0.028486170309586
	Guided bus 1	9715661000	0.00279633627537078
	Guided bus 2	9715661000	0.00316874571034682
	Guided bus 3	9715661000	0.00293667635515871
	Guided bus 4	9715661000	0.0107105467840579
	BRT	9715661000	-0.00154744023541054
Whole Line	Do-nothing	5412583000	-0.0444385166304621
	LRT	25822639000	0.0304282374029314
	Guided bus 1	11559510000	0.00220977483869385
	Guided bus 2	11559510000	0.00270856838868213
	Guided bus 3	11559510000	0.00239177997493904
	Guided bus 4	11559510000	0.00957531410006564
	BRT	11559510000	-0.00287515807484997
Battery Park Line	Do-nothing	2137863300	-0.0477357420587346
	LRT	19414915000	0.0281363484324837
	Guided bus 1	8139704000	0.00324016388305333
	Guided bus 2	8139704000	0.00359244759413921
	Guided bus 3	8139704000	0.00337155802169916
	Guided bus 4	8139704000	0.0102054732674944
	BRT	8139704000	-0.000810249140135151

In this Table, the strikethroughs in the alternative system column are the alternative systems over the available budget, which are not feasible and would not be considered further, and the shaded areas in the *alternative system* column are the best alternative systems for each basic line of the Damsui extension line.

Finally, the DSS will provide a comparison of the set of best alternative transit systems for all the alternative lines studied so that the user can find a combination of a line and a transit system that represent the most appropriate solution for the study area. The results of the Damsui extension line demonstration are shown in Figure 6.3.9, and the most appropriate solution can be chosen by the user. From the index ranking, the combination of the ‘Blue Ocean Line – Tai 2 Line’ and ‘LRT’ is chosen as the most appropriate solution for this case. The final results are shown in Figure 6.3.10 which displays the most appropriate combination of a line and a medium-capacity transit system, as well as information on costs and revenues to the user.

Figure 6.3.9 Comparison of Best Alternative Systems for the Basic Lines Analyzed

Figure 6.3.10 Result of the Most Appropriate Solution for the Damsui Case

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

This study aims to develop a methodology to assist urban planners in choosing an optimal medium-capacity transit system with good performance and sustainability as well as a decision support system built with C# language to facilitate this task. From a review of the literature, four main medium-capacity transit systems are included in the DSS as built-in transit system alternatives. These are *BRT*, *LRT*, *Guided Bus*, and *LRRT (AGT)*. Several system attributes were selected from many performance and sustainable factors for comparing and evaluating these alternative systems so that the most appropriate transit system for the study area may be selected. The DSS also includes some default values for various attributes associated with the evaluation of these alternative systems for use by users who do not have their own site-specific data. A method is developed in this study which minimizes the weakness of the original MEQQD method and makes it possible to meaningfully integrate all the system attributes considered. As the name implies, a DSS is a system to support users in decision-making rather than making decisions for them. The DSS developed in this study merely provides the finance and index ranks of each alternative for the user who will then select the best alternative system. Finally, a demonstration of the DSS is done by using the data of the extension line of Damsui rapid transit in Taiwan.

7.1 Conclusions

Some conclusions from this study are presented in the following sections.

1. In past studies, there is a lack of comparative study of medium-capacity transit systems based on an evaluation of multiple system attributes simultaneously.

The evaluation performed in these studies usually compared only one or a few attributes. Although some studies used several attributes for comparison, the alternative systems were compared qualitatively on an attribute-by-attribute basis rather than having all attributes combined into a quantitative and objective value for evaluation. In this study, a method is developed to compare medium-capacity transit systems by considering simultaneously multiple system attributes through integrating all attributes into an index. This provides users with a much clearer comparison of alternative systems. Furthermore, the technical feasibility of each alternative system is assessed first to ensure that all alternative systems can be developed technically.

2. Some researchers have applied the MEQQD method to compared alternatives. MEQQD uses normalization to establish dominance levels for the attributes, and considers only the relativities between alternatives for the same attribute. However, the same dominance level for different attributes does not have the same meaning, so MEQQD is not suitable for comparing alternatives with attributes which are measured in different units. The improved MEQQD method developed in this study is able to alleviate this problem -- by expressing as many quantitative attributes as possible into the same monetary units to eliminate the need to standardize attributes. This makes it possible to integrate all quantitative and qualitative forms of the system attributes into a single index for evaluation.
3. Subjective assignment of attribute weighting is used in this study to place due emphasis on the opinion of the system user. The user is asked to provide the relative importance of the system attributes, and the Weighted Least-Squares

Method is then applied to establish the weighting assigned to each attribute.

4. In the evaluation of medium-capacity transit systems, the “do-nothing” case is also included as an alternative because, in some cases, it might be more suitable for the study area to maintain the status quo rather than to develop a new system.
5. The system attributes used in this study are grouped under the categories of ‘performance’ and ‘sustainability’. The selected system attributes are:
 - (1) Performance:
 - a. System performance: line capacity, reliability, and travel time (system efficiency).
 - b. Vehicle performance (these attributes are only used for assessing technical feasibility of each alternative system): required minimum radius and maximum gradient.
 - (2) Sustainability:
 - a. Economic sustainability: costs, revenues, CO₂ emissions and congestion (when these are expressed in monetary value).
 - b. Social sustainability: Congestion (when expressed in travel time or delay), potential of increased business opportunity, system safety and passenger safety.
 - c. Environmental sustainability: CO₂ emissions (when these are expressed in quantitative amounts), air pollution, and noise.
6. Peak and off-peak traffic conditions are taken into account in the calculation of

attribute measures to better reflect the issue of *Congestion* which may arise if average or total trip data is used because they do not reflect the peaking characteristics of traffic, and usually there is little congestion during off-peak hours. In addition, the amounts of *CO₂ Emission* and *Air Pollution* are affected by vehicle speeds. Therefore, by using both peak and off-peak traffic conditions, a more realistic evaluation can be achieved.

7. The DSS provides options for the users to use either site-specific data if these are available to them, or use default values that are built into the system. The latter comes from the average or general values extracted from the literature and past studies in transit system planning. It is helpful to users if they do not have information about the alternative systems. Some of the required information also provides more details for the user in entering data. For example, if the user does not have information on total system cost, the DSS divides this into detailed parts such as land acquisition, way construction, etc. to assist the user in data input.
8. The DSS evaluates not only alternative systems for the same basic line but also the same alternative systems for different lines, as well as different alternatives for different lines. Thus, the DSS is able to assist the user in finding an optimal combination of a line and a medium-capacity transit system for the study area that is the most suitable among all alternative transit systems investigated.
9. For the demonstration of the DSS by applying the data of the extension line of Damsui transit system, results from the DSS suggest that using *LRT* for the *Blue Ocean Line – Tai 2 Line* is the optimal combination of transit line and

medium-capacity transit system for that study area.

10. The DSS is an easy-to-use tool for users who wish to evaluate many attributes simultaneously in order to select an optimal transit system for the study area that will be sustainable and will offer good performance.

7.2 Recommendations for Further Study

Some limitations of this study and recommendations for further work are described in the following sections.

1. In computing the attribute measure for *Air Pollution*, all air pollutant emissions are lumped together as total air pollutants. In fact, the degree of damage to human health by different air pollutants is not the same. It would be more reasonable to account for the different degrees of damage of each air pollutant.
2. The default values used in this study are averages of the data obtained from the literature and reports of other studies. There is generally a lack of information on energy consumption and noise for the transit systems studied, so the amount of data is limited and this may lead to rather inaccurate estimation of averages of these parameters. Furthermore, the transit vehicles planned to be used in the various reports/studies are not the same, so the average or default values for these attribute measures are not representative of any particular vehicle and may not be representative of the specific vehicles considered by the user for his study. Therefore, users would need to do additional study after using this DSS to make sure that the attribute measures are realistic if these are considered important.

3. It was very difficult to obtain detailed information on capital and replacement costs of each facility because such information is not generally available and most of these are also confidential. Therefore, the DSS is not able to provide the default values of detailed costs. However, users normally only do studies for some of the alternative systems, and is not likely to have information on the costs of other alternative systems built into the DSS. Therefore, the DSS can be much more effective if it provides more accurate default values to users.
4. Several default values (e.g., CO₂ emission, air pollution, capacity, minimum radius, maximum gradient, etc.) will most likely change in the future due to technological advances. Therefore, the DSS should be updated regularly in the future.
5. The concepts of the DSS development and improved MEQQD can be applied in future studies for comparing alternatives by using multi-attributes which include both qualitative and quantitative types.
6. Although the user is given control on the assignment of weights to attributes in this study, the set of attributes used in the comparison of alternatives is however decided by this study rather than by the user. The DSS could be made more flexible if the user has the option to eliminate some attribute or add attributes that they are interested in. There is no limit on the number of system attributes that can be taken into consideration. The drawback if this function is added would be the need for the user to provide the measures of the new attributes since obviously it would not be possible to have these built into the DSS.

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Appendix A Information from Review of Literature and Cases

1. Transport-Related Sustainability Indicators Used in Past Studies

Table A.1 Transport-Related Quality-of-Life Indicators (UK, 1999)

Objectives	Topics	Indicators
Sustainable Economy	Economic Stability and Competitiveness	Social investment (roadway, bus, rail related) proportion of GDP
	Sustainable Production and Consumption	Consumer expenditure in commute
		Energy efficiency of road freight transport
		Sustainable tourism
		Leisure trips by mode of transport
		Overseas travel
		Freight transport by mode
		Heavy goods vehicle mileage intensity
Building Sustainable Communities	Travel	Passenger travel by mode
		How children get to school
		Average journey length by purpose
		Traffic congestion
		Distance travelled relative to income
	Access	People finding access difficult
		Access to rural service
		Access for disabled
	Local Environment Quality	New retail floorspace in town centers and out of town
		Noise levels
Managing Environment and Resources	Climate change and energy supply	Carbon dioxide emissions by end user
	Air and atmosphere	Concentrations and emissions of selected air pollutants (NO ₂ , SO ₂ , CO, PM ₁₀ , O ₃ , and NO _x)
Sending the Right Signals	Sending the Right Signals	Prices of key fuel (petroleum oil/ diesel oil)
		Real changes in the cost of transport
		Public understanding and awareness
		Individual action for sustainable development

Table A.2 Transport-Related Urban Sustainability Indicators (Taipei, 1996)

Indicator Groups		Name of Indicators	Evaluating Methods	Main Indicators
Urban System	Transport	Automobile ownership ratio	(Number of automobiles/population) *1000	√
		Public transit mobility	Number of passengers/transit-kilometer	√
		Commuting time	Average commuting time per person per day	
		Average travel speed in peak hour	Average travel speed on arterial and secondary arterial in peak hour	
		Length of bikeway	The length of bikeway	
	Land Use	Ratio of public facility area	(Public facility area/total land area) *100%	√
		Length of pedestrian mall	Length of pedestrian mall	
	Environmental Quality	The no. of heavy air pollution days per year	Number of day per year with PSI > 100	√
		Ratio of annual noise pollution	(Number of times that monitored Leq exceed standard Leq/the total no. of monitoring times) *100%	
		Ratio of acid rain days per year	(Number of monitored acid rain days/the no. of monitoring days) *100%	
	Safety	Traffic accident rate	Number of traffic accidents/ the no. of total vehicles	
	Public Welfare	Ratio of barrier free facilities	(Number of buildings with barrier free facilities/ Number of total building) *100%	√
Resource Input		Fuel consumption per person	Fuel consumption/ population	√
Urban Waste Treatment and Output		Air pollution per person	Total emissions of air pollution/population	
		CO ₂ emission	Σ (each kind of energy consumption* emissions by each kind of energy per unit)	
Environmental Management		Expenditure ratio for environmental protection by public sector	(Environmental protection expenditure/ total expenditure) * 100%	√

Table A.3 Sustainability Indicators for Evaluating Transit Modes

(Hsu and Liu, 2004)

Types of Sustainability	Indicators
Environmental Sustainability	Energy consumption
	Greenhouse effect
	Air pollution
	Noise
	Congestion
	Accident
Social Sustainability	External costs (negative impacts to people caused by transport activities, including air pollution, noise, congestion, roadway investment costs, etc.)
	Access difficulty to the disabled
Economic Sustainability	Costs
	Travel time

2. Review of Transit System Cost Components

Table A.4 Components of Transit System Cost Function (Brems, 1980)

$C = A + ax$				
Costs			Unit	Inclusion
fixed	line-acquisition (A)		\$ / (line km-year)	All investment cost except vehicle-acquisition cost, including ROW, construction, etc.
variable	traffic (a)	vehicle acquisition	\$/passenger-space km	Vehicle purchase costs
		operation & maintenance		Including all costs for operation / maintenance tasks

Table A.5a Transit System Investment Cost Components (Vuchic, 2007)

Item	Inclusion	Comment
ROW acquisition	Land purchases for ROW	No direct cost for underground and the use of public ROW
	Land purchases for station space	
Permanent way construction	Site preparatory works	Elevated structures cost 2 to 3 times higher than at-grade systems, but is at least 2 to 3 times cheaper than underground construction.
	Line infrastructure	
	Restoration of street and sidewalk	
	Construction of plazas and landscaping	
Station construction	All station construction costs (platforms, walkways, stairways, escalators, fare collection barrier, corridors, parking lots)	Vary among modes and positions relative to location, type (surface, underground, or aerial) and surroundings.
Track superstructure	Tracks, switches, crossovers, and related equipment	-
Power supply	Substations, distribution system, third rail or overhead wire	
Control and communications	Signal system, communications, and emergency systems	-
Vehicle	Vehicle purchase costs	Depends on design, complexity and number of vehicle ordered.
Maintenance / storage facilities	All maintenance and storage facilities, including shops, yards and administrative	Depend on site location and shape, type of maintenance and capacity.
Engineering and administration	Agency costs in implementing the facility	-
Contingencies	Unpredictable costs	25% initially decrease to 10%.

Table A.5b Transit System Operating/Maintenance Costs (Vuchic, 2007)

Item	Inclusion	Comment
Contingencies	Unpredictable costs	25% initially decrease to 10%.
Vehicle operations	Wages of personnel involved in operation, such as drivers, supervisors, station attendants, and scheduling personnel	
Power	Cost of electricity or fuel	
Vehicle and Permanent-way maintenance	Personnel and material costs for maintenance, repair, testing, and cleaning of cars; and. to maintain the permanent way, including racks, power supply, signals, etc.	
General and administration	Indirect operating costs (management, legal, accounting, insurance, staff benefit, building/ground maintenance, miscellaneous costs)	

3. Review of Information for Walking Time Calculation

Table A.6 Guidelines/Studies on Walking Distance

(O'Sullivan and Morrall, 1996)

Areas	Walking Distance Guidedlines
Calgary Transit, Canada	General Guideline: 400 m
British. Columbia. Transit, Vancouver, Canada	Guideline For LRT: 900 m
Montreal, Canada	General Guideline: 400-500 m
Ottawa-Carleton Regional Transit Commission	General Guideline: 400-600 m
Toronto Transit Commission, Canada	Guideline for Surface Transit: 300 m
Edmonton Transportation, Canada	General Guideline: 400 m
Niagara Frontier Transportation Authority, USA	General Guideline: 457 m
Denver Regional Transportation District, USA	General Guideline: 536 m
New Jersey Transit, USA	General Guideline: 804 m
Sacramento Regional Transit Distinct, USA	64% of users walk < 403 m; 90% < 804 m. Regional Transit Guideline: 609 m.
Metropolitan Transit Development Board, San Diego	General Guideline: 538 m
Calgary LRT, Canada	Average walking distance to suburban station: 649 m,. CBD station: 326 m.

Table A.7 Average Pedestrian Walking Speeds (Chu, 2008)

Researcher	Average Walking Speed	Location	Country
Older (1968)	1.30 (free flow speed)	Commercial area	Germany
Fruin (1971)	1.4	Commuter station	the US
Henderson (1971)	1.44	Sidewalk	Australia
Tsay (1979)	1.13	Sidewalk	Taiwan
Tanariboon et al. (1986)	1.23	Commercial area	Singapore
Chen (1986)	1.25	Sidewalk	Taiwan
Tanariboon et al. (1991)	1.22	Sidewalk	Thailand
Lam et al. (1995)	1.19	Sidewalk	Hong Kong
Wu (1998)	1.2	Tourist hotel	Taiwan
Hsu (1998)	1.21	MRT corridor	Taiwan
Lai (2000)	1.51	MRT corridor	Taiwan
Lin (2001)	1.38	MRT corridor	Taiwan

4. Review of Average Wage Rates in Taiwan for VOT Calculation

Table A.8 Average 2008 Wage Rates in Taiwan (DGBAS, 2009)

Average wage	252.88	7.5
Unit	TWD/hr	USD/hour

5. Review of Factors Affecting Accessibility of Transit Systems

Table A.9 Descriptions of Factors which Affect Accessibility

Name	Description
Transport Demand	Amount of mobility and access that people and businesses would choose under various conditions (times, prices, levels of service, etc).
Mobility	Distance and speed of travel, including personal mobility (measured as person-km) and vehicle mobility (measured as vehicle-km).
Transportation Options	Quantity and quality of access options, including walking, cycling, ridesharing, transit, taxi, delivery services, and telecommunications. Qualitative factors include their availability, speed, frequency, convenience, comfort, safety, price and prestige.
User information	Quality (convenience and reliability) of information available to users on their mobility and accessibility options.
Integration	Degree of integration among transport system links and modes, including terminals and parking facilities.
Affordability	Cost to users of transport and location options relative to incomes.
Mobility Substitutes	Quality of telecommunications / delivery services that substitute for physical travel.
Land Use Factors	Degree that factors such as land use density and mix affect accessibility.
Transport Network Connectivity	Density of connections between roads and paths, and directness by which people can travel between destinations.
Roadway Design and Management	How road design and management practices affect vehicle traffic, mobility and accessibility.
Prioritization	Various strategies that increase transport system efficiency.
Inaccessibility	Value of inaccessibility and external costs of increased mobility.

6. CO₂ Emission Calculation:

Information and data about CO₂ emission and energy consumption by road transport (passenger cars, motorcycles, and regular buses) and vehicles of alternative transit systems (including BRT by fuel, LRT and LRRT, and electric guided-buses) are collected from a review of literature, vehicle manufacturer publications, or statistical data from governments. Some sources calculated CO₂ emission per kilometer, while others presented these in other units or forms that need to be converted to the same unit for comparison. The CO₂ emission data, calculation procedure, and the CO₂ emission calculated for each mode are described in the following.

(1) Road Transport:

Road transport in this study include: (a) passenger vehicles, which contain passenger cars and motorcycles, and (2) regular buses, which are the most frequently used existing transit systems before the implementation of medium-capacity transit systems in the world. The data needed for, and the procedure of, CO₂ emission calculation are presented here.

a. Car and Motorcycle

The conversion factors for passenger cars and motorcycles in CO₂ emission per kilometer are dependent on vehicle speed (v in km/h) as shown below:

$$EF(g \text{ CO}_2/\text{km}) = (a + b*v + c*v^2 + d*v^e + f*\ln(v) + g*v^3 + h/v + i/v^2 + j/v^3)*x$$

The factors were developed by NETCEN under the National Atmospheric Emissions Inventory Programme in consultation with UK's Transport Research Laboratory (TRL) from their analysis of emission test results on vehicles meeting

Euro II or Pre-2000 standards (NETCEN, 2003). These are presented in Table A.10.

Table A.10 Vehicle Speed-Emission Factors (NETCEN, 2003)

Vehicle	Vehicle Size	a	b	c	d	e	f	g	h	i	j	x
Petrol car ^a	< 1.4 l	29.33	-0.004	0.000	0	0	0	1.377E-05	542	0	0	3.14
	1.4 - 2.0 l	36.25	0.000	0.000	0	0	0	1.321E-05	655	12.2	0	3.14
	> 2.0 l	80.36	-1.049	0.008	0	0	0	2.017E-08	612	0	0	3.14
Motor-cycles ^b	moped (2-s)	25	0	0	0	0	0	0	0	0	0	3.14
	<250cc 4-s	70.78	-2.25	0.032	0	0	0	-1.31E-04	0	0	0	3.14
	250-750cc 4-s	102.10	-3.32	0.045	0	0	0	-1.86E-04	0	0	0	3.14
	>750cc 4-s	119.63	-3.63	0.048	0	0	0	-1.95E-04	0	0	0	3.14

Note: a -- Euro II; b – pre-2000

The UK Department for Environment Food and Rural Affairs (Defra) used vehicle registration data from 1997 to 2007 from the Society of Motor Manufacturers and Traders Limited to calculate the percentage of various sizes of petrol cars, which are shown in Table A.11.

Table A.11 Total Registrations and Percentage of Various Petrol Cars (Defra, 2008)

Petrol car	< 1.4 l	1.4-2.0 l	> 2.0 l
Total no. of registrations	8,417,053	9,312,278	1,765,218
% Total	43%	48%	9%

In this study, the speed-emission factors of passenger cars are calculated from the average of each size of petrol cars using the information in Tables A.10 and A.11. The results are shown in Table A.12.

Table A.12 Speed-CO₂ Emission Factors for Passenger Cars

Vehicle Size	%	a	b	c	d	e	f	g	h	i	j	x
<1.4 l	43%	29.33	-0.004	0.000	0	0	0	1.377E-05	542	0	0	3.14
1.4-2.0 l	48%	36.25	0.000	0.000	0	0	0	1.321E-05	655	12.2	0	3.14
> 2.0 l	9%	80.36	-1.049	0.008	0	0	0	2.017E-08	612	0	0	3.14
Average	100%	37.25	-0.096	0.00072	0	0	0	1.23E-05	602.314	5.871	0	3.14

As information on motorcycle registrations is not available to this study, the speed-emission conversion factors for motorcycles were assumed as the average of each size of motorcycle in Table A.10 and shown in Table A.13.

Table A.13 Speed-CO₂ Emission Factors for Motorcycles

Vehicle Size	%	a	b	c	d	e	f	g	h	i	j	x
moped (2-s)	25%	25	0	0	0	0	0	0	0	0	0	3.14
<250cc 4-s	25%	70.78	-2.25	0.032	0	0	0	-1.31E-04	0	0	0	3.14
250-750cc 4-s	25%	102.10	-3.32	0.045	0	0	0	-1.86E-04	0	0	0	3.14
>750cc 4-s	25%	119.63	-3.63	0.048	0	0	0	-1.95E-04	0	0	0	3.14
Average	100%	79.378	-2.299	0.031255	0	0	0	-0.00013	0	0	0	3.14

The demand of a planning area in this study is computed in passenger trips. But the CO₂ emissions are based on distance travelled by vehicles. This means vehicle load factors are needed to convert passenger trips to vehicle trips which, in turn, provides vehicle distance travelled. Average load factors used in here are extracted from the Taiwan Ministry of Transportation and Communications (MOTC) (see Table A.14). The average load factor of passenger cars were computed by excluding commercial vehicles which accounted for 2.46%.

Table A.14 Passenger Car and Motorcycle Load Factors in Taiwan in 2006

(MOTC Website)

Vehicle Type		Load Factor	Percent	Average Load Factor
Passenger Car	< 1800cc	1.5 persons	54.58%	1.73 persons/vehicle
	1800-2400cc	2.0 persons	34.38%	
	> 2400cc	2.1 persons	8.58%	
Motorcycle	Light-Duty (<=50cc)	1.2 persons	33.72%	1.13 persons/vehicle
	Heavy-Duty (> 50 cc)	1.1 persons	66.28%	

b. Regular Bus

Similarly, the speed-CO₂ emission factor for regular buses used in this study was also developed by NETCEN from their analysis of emission test results on vehicles meeting Euro II standards (NETCEN, 2002). This is presented in Table A.15. The load factors of regular buses for Taiwan and USA are given in Table A.16.

Table A.15 Calculation of Speed-CO₂ Emission Factors for Regular Buses

Reference	a	b	c	d	e	f	g	h	i	j	x
Euro II	200.3	2.93E-04	-0.0156	0	0	0	1.75E-04	26.0	29113	-111672	3.14

Table A.16 Average Load Factors for Regular Buses in Different Areas

Area	Load Factor (passenger/vehicle)	Reference
Urban Areas in Taiwan (2007)	19	MOTC Website
USA (2006)	9	APTA, 2008

(2) Medium-Capacity Transit Systems

In this study, alternative medium-capacity transit systems include BRT, guided bus, LRT, and LRRT and AGT. Among these alternatives, BRT use fuel, while guided bus can be operated by both fuel and electricity, and LRT, LRRT and AGT are operated by electricity. As most of these medium-capacity transit systems usually operate on exclusive roadway, we assume that the CO₂ emissions per km of alternatives using electric power and LRV (Light Rail Vehicle) including LRT, LRRT, and AGT are the same, and the CO₂ emission per km of systems using bus vehicles powered by fuel including BRT and some guided bus are also the same.

The calculation of CO₂ emission for medium-capacity transit systems are divided into systems that use fuel and those that use electricity. Systems that use electricity

can further be classified into guided bus and LRT vehicles (LRT, LRRT, and AGT).

a. Systems that Use Fuel (BRT and Guided Bus that Use Fuel)

Although BRT and guided bus that use fuel are similar to a regular bus powered by fuel, several factors such as operating speed, acceleration and deceleration do affect energy consumption which results in different CO₂ emissions. Furthermore, regular buses typically use diesel, while today's new bus systems may use several other types of fuels, so new BRT and guided buses have wider choices of fuel. The CO₂ emission conversion factors for various fuels are shown in Table A.17.

Table A.17 CO₂ Emission Conversion Factors for Fuels (DEFRA, 2007)

Fuel Type	Units	kg of CO₂ per unit
Diesel	litres	2.630
Natural Gas (CNG)	m ³	2.190 ^{note}
LPG	litres	1.498
Gasoline	litres	2.674

Note: CO₂ emission conversion factor for natural gas by DEFRA is 6.023 (kg/therm), and 1 therm of gas equals to 2.75 m³. Therefore, conversion factor for natural gas is 2.190(kg/m³)

Both BRT and guided buses by fuel operate on exclusive roadways. Hence their speeds in the peak and off-peak periods are similar. It is difficult to collect data on CO₂ emissions and energy consumption of BRT and guided buses. This study will try to use available information to do estimation. These include: (1) CO₂ emissions or energy consumptions of regular buses of different sizes using different fuels (see Table A.18, and the calculated average of each type of bus vehicles in TableA.19); (2) fuel consumption comparison between regular bus and BRT using the same Volvo 7500 bi-articulated diesel bus (from Jobson, 2008) which indicated that the regular bus consumes 0.772 liters/km of fuel and BRT consumes 0.469 liters/km.

Therefore, it is assumed that the CO₂ emission of BRT can be calculated by applying the ratio $\left(\frac{0.469}{0.722}\right)$ to the CO₂ emission of a regular bus. The calculations for each type of buses are shown in Table A.20, with Jobson's results for the Volvo 7500 bi-articulated diesel bus shown in bold.

Table A.18 CO₂ Emissions and Energy Consumptions of Regular Buses

Fuel	Area	Type	Size	Energy Consumption	kg of CO ₂ per km
Diesel	Santa Barbara, CA, USA	MCI 102DL3	Standard	0.392 (l/km) (CA Energy and ABAPCD, 2000)	1.031
	Urban Areas in Taiwan	Average	Standard	0.450 (l/km) (MOTC website)	1.183
	Sweden	Maximum	Standard	0.532 (l/km) (Andersson and Gibrand, 2008)	1.399
	Vancouver	-	Standard	0.639 (l/km) (BC Transit website)	1.681
	OC Transpo	-	Standard	0.588 (l/km) (Lane, 2007)	1.546
	-	New Flyer	Articulated	-	2.869 (Vincent and Jerram, 2006)
	Mexico City	-	Articulated	0.654 (l/km) (INE, 2008)	1.720
	-	-	Articulated	0.6 (l/km) (Mackinger, 2006)	1.578
	OC Transpo	-	Articulated	0.833 (l/km) (Lane, 2007)	2.191
	-	Van Hool AGG 300	Bi-articulated	0.75 (l/km)	1.973
		Volvo 7700	Standard	0.472 (l/km) (Jobson, 2008)	1.241
		Volvo 8700	Standard	0.430 (l/km) (Jobson, 2008)	1.131
		Volvo 7500	Bi-articulated	0.722 (l/km) (Jobson, 2008)	1.899
CNG	-	-	Standard	-	0.954 (Vincent and Jerram, 2006)
	Mexico City	-	Standard	0.455 (m³/km) (INE, 2008)	0.996
	Sweden	Minimum	Standard	0.486 (m³/km) (Andersson and Gibrand, 2008)	1.064
		Maximum		0.541 (m³/km) (Andersson and Gibrand, 2008)	1.185
LPG	Mexico City	-	Standard	0.876(l/km) (INE, 2008)	1.312

Table A.19 Average CO₂ Emissions for Various Types of Regular Buses

Type	Size	Energy Consumption (l/km)	Kg of CO ₂ per km
Diesel	Standard	0.500	1.316
	Articulated	0.794	2.088
	Bi-articulated	0.736	1.936
CNG	Standard	-	1.050
LPG	Standard	0.876	1.312

Table A.20 Average CO₂ Emissions of BRT and Guided Bus that Use Fuel

Fuel	Area	Type / Size	Energy Consumption (kg of CO ₂ /km)	
			Regular bus	BRT
Diesel	Santa Barbara, CA, USA	MCI 102DL3 / Standard	0.392 (1.031)	0.255 (0.670)
	Urban Areas, Taiwan	Average / Standard	0.450 (1.183)	0.292 (0.768)
	Sweden	Maximum / Standard	0.532 (1.399)	0.346 (0.909)
	Vancouver	-- / Standard	0.639 (1.681)	0.415 (1.092)
	OC Transpo	-- / Standard	0.588 (1.546)	0.382 (1.004)
	-	Volvo 7700 / Standard	0.472 (1.241)	0.307 (0.806)
	-	Volvo 8700 low entry / Standard	0.430 (1.131)	0.279 (0.735)
	-	New Flyer / Articulated	- (2.869)	0.709 (1.864)
	Mexico City	-- / Articulated	0.654 (1.720)	0.425 (1.117)
	-	-- / Articulated	0.600 (1.578)	0.390 (1.025)
	OC Transpo	-- / Articulated	0.833 (2.191)	0.541 (1.423)
	-	Van Hool AGG 300 / Bi-articulated	0.750 (1.973)	0.487 (1.282)
		Volvo 7500 / Bi-articulated	0.722 (1.899)	0.469 (1.234)
CNG	-	2000 DDC Series 50G engine / Standard	- (0.954)	0.283 (0.620)
	Mexico City	CNG / Standard	0.455 (0.996)	0.296 (0.647)
	Sweden	Natargasbuss (Min) / Standard	0.486 (1.064)	0.316 (0.691)
		Natargasbuss (Max) / Standard	0.541 (1.185)	0.351 (0.770)
LPG	Mexico City	LPG / Standard	0.876 (1.312)	0.569 (0.852)

In addition, some BRT vehicles have directly measured energy consumption and

emission data (see Table A.21). Therefore, the average CO₂ emission for each type of BRT vehicle can be computed. These are summarized in Table A.22.

Table A.21 CO₂ Emission of BRT

Area	Size	Energy Consumption (l/km)	kg of CO ₂ per km	Reference
-	Standard	0.358	0.942	Andersson and Gibrand, 2008
Latin America	Articulated	0.55	1.447	Diamler, 2008
Europe	Articulated	0.52	1.368	Diamler, 2008
South Africa	Articulated	0.52	1.368	Diamler, 2008

Table A.22 Average CO₂ Emission of BRT Vehicles

Type	Size	Energy Consumption	kg CO ₂ per km
Diesel	Standard	0.329 (l/km)	0.866
	Articulated	0.522 (l/km)	1.368
	Bi-articulated	0.478 (l/km)	1.258
CNG	Standard	0.312 (m ³ /km)	0.682
LPG	Standard	0.569 (l/km)	0.852

b. Systems that Use Electricity (LRT Vehicle and Electric Guided-Bus)

The amounts of CO₂ emissions of alternative transit systems propelled by electricity depend on the source of material for electricity generation and the electricity consumption of vehicles. Table A.23 and Figure A.1 present the life cycle CO₂ emission for each type of electricity generation. The user can refer to Table A.23 to calculate the CO₂ emission per kWh for the area studied by the proportion of different sources of electricity. In this study, the default CO₂ emission per kWh for electric power is set at **0.5775 kg of CO₂ per kWh**. This is the average of data from the UK and Taiwan, which are 0.523 and 0.632 kg of CO₂ per kWh (see Tables A.24 and A.25).

Table A.23 Life-Cycle CO₂ Emission for Electricity Generation (WNA, 2008)

Source of Electricity	CO ₂ Emission (g per kWh)			
	Japan	Sweden	Finland	Average
Coal	975	980	894	950
Gas thermal	608	-	-	608
Gas combined cycle	519	450	472	480
Solar PV	53	50	95	66
Wind	29	5.5	14	16
Nuclear	22	6	18	15
Hydro	11	3	-	7

Figure A.1 Life Cycle CO₂ Emission for Electricity Generation (WNA, 2008)

Table A.24 UK Electricity Conversion Factors of CO₂ Emission (DEFRA 2007)

Year	2001	2002	2003	2004	2005	Average
g of CO ₂ per kWh	525.81	509.74	526.28	526.59	526.57	523.00

Note: The electricity conversion factors given are the average carbon dioxide emission from the UK national grid per kWh of electricity used at the point of final consumption.

Table A.25 Electricity CO₂ Emission Conversion Factor (Taipower Website)

Year	2005	2006	2007	Average
kg CO ₂ per kWh	0.620	0.638	0.637	0.632

b-1. LRT

Table A.26 shows the electricity consumption of various types of LRT for a few areas. In this study, the default electricity consumption for an LRT with 200 spaces per TU is 2.56 kWh per km. LRT CO₂ emissions per TU per km can be obtained with the use of electricity conversion factors for CO₂ emission for these areas.

Table A.26 LRT Electricity Consumption

Area	LRT Vehicle Type	Capacity (spaces/TU)	Electricity Consumption (kWh/km)	Reference
Basel, Switzerland	Siemens, Combino LRV	180 spaces	1.53	Siemens Website
Potsdam, Germany	Siemens, Combino LRV	180 spaces	1.84	Strickland, 2009
Calgary, Canada	Siemens, U2	200 spaces	3.23	Calgary Transit Website
Calgary, Canada	Siemens, SD160	200 spaces	3.23	Calgary Transit Website
Vancouver	Skytrain	110 spaces	2.41	T2000BC, 1994
Göteborg, Sweden	Spårvagn, average	180 spaces	3.15	Andersson & Gibrand, 2008
Average LRT Electricity Consumption (kWh/km)			2.56	CO₂ emission: 1.478 kg/km

b-2. Electric Bus (Guided Bus that Uses Electricity)

Some guided buses are powered by electricity. Due to their scarcity, it is difficult to find their electricity consumption data. Therefore, electricity consumption data for trolleybuses (Table 27) are used for electric guided buses. This yielded average electricity consumption rates of 1.985 and 2.3 kWh/km, respectively, for standard and articulated buses which are used as default values in this study. CO₂ emission per km for an electric guided bus is estimated using the electricity conversion factors of CO₂ emission for each area.

Table A.27 Electric Bus Energy Consumption

Area	Electric Trolleybus	Size and Capacity	Electricity Consumption (kWh/km)	Reference
-	-	Standard	1.8	Nylund et al., 2004
Vancouver, Canada	New Flyer	77 spaces	2.14	Strickland, 2009
Sweden	Trådbuss	Standard	Min (1.8); Max (2.2)	Andersson and Gibrand, 2008
Salzburg	Trolleybus	Articulated	2.3	Mackinger, 2006
Average Electricity Consumption (kWh/km): Standard bus 1.985; Articulated bus 2.3				
Average Electric Bus CO₂ Emission (kg/TU-km): Standard bus 1.146; Articulated bus 1.328				

After obtaining the CO₂ emissions for the alternative transit systems, one needs to convert these CO₂ emission amounts to prices for areas which engage in carbon trading. Figure A.2 shows the carbon trading prices from January 2006 to April 2009 extracted from the European Community Exchange website. The average front settlement price from the beginning of 2009 to 16 April 2009, which is € 11.40 per ton CO₂, is set as the default pricing in this study.

Figure A.2 EU Carbon Trading Prices from Jan 06 to Apr 09 (ECX Website)

7. Air Pollution

The air pollution emission results from Delucchi (2006) covered CO, NO_x, SO_x, PM, CH₄, N₂O, NMHC, NMOG, C₆H₆, CH₂CHCHCH₂, HCHO, CH₃CHO, and CH₂CH₂ emissions by fuel in g/km for each transport mode at a speed of **55 mph**; and for each type of electricity generation in g/kWh. It is noted that the damage to human health of these air pollutants and the way that air pollutants are calculated vary by area. In addition, Delucchi's results gave the same air pollutant emissions regardless of whether electricity or fuel is used. Hence, for comparison purpose in this study the air pollutant values are the sum of all air pollutants in grams.

The amounts of air pollution from road transport modes (passenger car, motorcycle, and regular bus) are also calculated separately for peak and off-peak periods. The speed differences between peak and off-peak periods are taken into consideration in the "air pollution" attribute calculation. Due to a lack of information on air pollutant emissions at different speed levels, the emission amounts are assumed in this study to be proportional to energy consumption. That is, given the air pollutant emissions in g/km for the various transport modes at 55 mph (88.5 kph), and the relationship between energy consumption and speed (i.e., speed-consumption factors) of each mode, energy consumptions for these modes at the same speed (55 mph or 88.5 kph) are calculated first. Then the energy consumptions for each transport mode at peak and off-peak speeds are calculated. This then allows the air pollutant emissions at a speed x kph (AP_x) from each road transport mode to be calculated using:

$$AP_x = AP_{88.5} \times (EC_x / EC_{88.5})$$

where AP_{88.5} = the amounts of air pollution at 88.5 kph (known);

$EC_x, EC_{88.5}$ = the amounts of energy consumptions at x kph and 88.5 kph respectively, (both known).

Note that the amounts of air pollutant emission from medium-capacity transit modes are similar for the peak and off-peak periods since speeds are similar.

With the estimated air pollutant emission rates in g/km for various transport modes, the total air pollutant amount from each mode can be computed by multiplying these rates with the total distance travelled by that mode. As with the calculation of CO₂ emission, computation of air pollutants also covers road transport and medium-capacity transit system.

(1) **Road Transport:**

a. Regular Bus

Air pollutant amounts from each type of regular buses at 55 mph (88.5 kph) are shown in Table A.28. As with the case of CO₂ emission, the air pollutant amounts for *diesel* which is the most commonly used fuel type is taken as the default values.

Table A.28 Air Pollutant Amounts for Buses in 55 mph (g/km) (Delucchi, 2006)

Pollutant	Air Pollutant Amounts for Buses (g/km)				
	Diesel	M85	LPG	CNG	E85
CO	12.5082	14.9502	7.9970	10.4266	14.9502
NO _x	11.3897	6.8351	5.6918	5.6918	6.8351
SO _x	0.0296	n.e.	n.e.	0.0000	n.e.
PM ₁₀	12.1416	10.9175	10.7684	10.8429	10.9175
CH ₄	0.1417	0.0708	4.2508	0.1417	0.0708
N ₂ O	0.0124	0.0124	0.0124	0.0124	0.0124
NMOG	2.9764	2.5166	0.1802	1.5037	4.2564
C ₆ H ₆	0.0319	0.0608	0.0013	0.0034	0.0355

HCHO	0.0875	0.3222	0.0389	0.0372	0.1064
CH ₃ CHO	0.0234	0.0122	0.0069	0.0140	0.4555
CH ₂ CHCHCH ₂	0.0425	0.0042	0.0000	0.0013	0.0059
CH ₂ CH ₂	0.0000	0.0547	0.0530	0.0857	0.2898
Total	39.3849	35.7020	28.9477	28.6750	37.6457

Table A.29 gives the speed-energy consumption factor for regular buses that meet the Euro II standards, and is prepared by NETCEN (2003). From Table A.29, the energy consumption at 55 mph (88.5 kph) is calculated to be 203.218 g of fuel/km.

Table A.29 Regular Bus Speed-Energy Consumption Factor (NETCEN, 2003)

Reference	a	b	c	d	e	f	g	h	i	j	x
Euro II	200.3	2.93E-04	-0.0156	0	0	0	1.75E-04	26.0	29113	-111672	1

For a given speed of operation v (in kph), the energy consumption at that speed can be calculated using the following:

$$EF = [a + bv + cv^2 + dv^e + f \ln(v) + gv^3 + h/v + i/v^2 + j/v^3]x \quad (\text{g of fuel/km})$$

The air pollutant emission, AP_x , at a speed x kph can then be calculated using:

$$AP_x = AP_{88.5} \times (EC_x / EC_{88.5}) = 39.3849 \times (EC_x / 203.218)$$

where EC_x = the amounts of energy consumptions at x kph (known)

b. Cars and Motorcycles

Table A.30 gives air pollutant amounts for passenger cars. As most passenger cars used gasoline, the total air pollutant amounts for gasoline, which is 5.0628 g/km, is set as the default air pollutant amounts for passenger cars.

Table A.30 Air Pollutant Amounts for Passenger Cars (g/km) (Delucchi, 2006)

Pollutant	Gasoline	M85	LPG	CNG	E85
CO	2.9577	1.6404	2.3426	1.9635	1.8890
NO _x	0.2423	0.2423	0.2423	0.2423	0.2423

SO _x	0.0042	0.0022	n.e.	0.0001	0.0018
PM ₁₀	1.5472	1.5410	1.5410	1.5410	1.5410
CH ₄	0.0230	0.0118	0.4629	0.0230	0.0118
N ₂ O	0.0311	0.0311	0.0311	0.0311	0.0311
NMOG	0.2361	0.0746	0.0249	0.0559	0.2485
C ₆ H ₆	0.0074	0.0020	0.0002	0.0001	0.0009
HCHO	0.0028	0.0104	0.0053	0.0014	0.0026
CH ₃ CHO	0.0008	0.0004	0.0009	0.0005	0.0112
CH ₂ CHCHCH ₂	0.0006	0.0001	0	0.0001	0.0001
CH ₂ CH ₂	0.0096	0.0017	0.0072	0.0031	0.0071
Total	5.0628	3.5580	4.6584	3.8621	3.9874

Table A.31 shows the speed-energy consumption factor for passenger cars meeting the Euro II standards, which is also prepared by NETCEN (2003). In computing the average values, the vehicle registration and percentage of each size of vehicle are the same as those used in computing the CO₂ emission (see Table A.12). Using the data in Table A.31, the average energy consumption at 55 mph (88.5 kph) is **49.706 g of fuel/km**. Energy consumption at any speed v (in kph) can be calculated using the formula below, and then the air pollutant emission at that speed can be computed.

$$EF = [a + bv + cv^2 + dv^e + f \ln(v) + gv^3 + h/v + i/v^2 + j/v^3]x \quad (\text{g of fuel/km})$$

Table A.31 Passenger Car Speed-Energy Consumption Factor
(NETCEN, 2003)

Reference	Vehicle Size	a	b	c	d	e	f	g	h	i	j	x
Euro II	< 1.4 l (43%)	29.33	-0.004	0.000	0	0	0	1.377E-05	542	0	0	1
	1.4 - 2.0 l (48%)	36.25	0.000	0.000	0	0	0	1.321E-05	655	12.2	0	1
	> 2.0 l (9%)	80.36	-1.049	0.008	0	0	0	2.017E-08	612	0	0	1
	Average	37.247	-0.096	0.00072	0	0	0	1.23E-05	602.314	5.871	0	1

No motorcycle air pollutant data is available. It is assumed that pollutant emission from motorcycles is directly related to their fuel consumption which can be obtained from the NETCEN (2003) speed-energy consumption factor (Table A.32).

Energy consumption of motorcycle at any speed v (in kph) can be obtained from the same formula shown above using the parameter values in Table A.32. The air pollutant emission from passenger cars at 88.5 kph is 5.0628 g/km and its corresponding energy consumption is 49.706 g of fuel/km. Therefore, the amount of air pollutant emission (AP_x) for motorcycle at any speed x (in kph) can be calculated using:

$$AP_x = AP_{88.5} \times (EC_x / EC_{88.5}) = 5.0628 \times (EC_x / 49.706)$$

where EC_x = the motorcycle energy consumptions at x kph (known).

Table A.32 Motorcycle Speed-Energy Consumption Factor (NETCEN, 2003)

Reference	Vehicle Size	a	b	c	d	e	f	g	h	i	j	x
Pre-2000	moped (2-s) (25%)	25	0	0	0	0	0	0	0	0	0	1
	<250cc 4-s (25%)	70.78	-2.25	0.032	0	0	0	-1.31E-04	0	0	0	1
	250-750cc 4-s (25%)	102.10	-3.32	0.045	0	0	0	-1.86E-04	0	0	0	1
	>750cc 4-s (25%)	119.63	-3.63	0.048	0	0	0	-1.95E-04	0	0	0	1
	Average	79.378	-2.299	0.031	0	0	0	-0.00013	0	0	0	1

(2) Medium-Capacity Transit Systems

a. Systems that Use Fuel (BRT and Guided Bus that Use Fuel)

There is also a lack of air pollution data for BRT. Therefore, the method to obtain the BRT air pollutant emissions is similar to that used in calculating the BRT CO₂ emission. That is, the energy consumption of the Volvo 7500 bi-articulated diesel bus is 0.722 ℓ/km when used as a regular bus and is 0.469 ℓ/km when used as BRT (Jobson, 2008). It is assumed that other types of buses have the same relationship as that of the Volvo 7500 bus. Therefore, the air pollutant emissions of BRT can be calculated by multiplying the air pollutants of a regular bus with (0.469 / 0.722). The results of BRT for various fuel types are shown in Table A.33.

Table A.33 Air Pollutant Emissions of BRT for Various Fuels (Delucchi, 2006)

	Air Pollutant Emissions for Regular Bus (g/km)				
	Diesel	M85	LPG	CNG	E85
Total	39.3849	35.7020	28.9477	28.6750	37.6457
$\times(0.469/0.722)$					
	Air Pollutant Emissions for BRT (g/km)				
Total	25.5838	23.1915	18.8040	18.6268	24.4541

b. Systems that Use Electricity (LRT Vehicle and Electric Guided Bus)

Table A.34 presents air pollutant emissions for various power plants, and Table A.35 shows the percentage of power plants using various electricity generation methods in the USA, as well as the calculated air pollutant emissions in g/kWh for each area. The average total air pollutant emission from these areas is 0.861 g/kWh. This is used as the default value of air pollutant emissions in this study.

Table A.34 Power Plant Air Pollutant Emission Rates (g/kWh) (Delucchi, 2006)

Power Plant	Coal DBPCB	Coal IGCC	NG boiler	NG turbine	NG CC	Fuel-oil boiler	Biomass
CO	0.0449	0.0062	0.0604	0.1702	0.1733	0.0511	0.1021
NO _x	0.7770	0.1470	0.4132	0.3405	0.3111	0.5200	0.1269
SO _x	1.4285	0.1161	0.0015	0.0015	0.0015	0.8187	0.0139
PM	0.0743	0.0155	0.0046	0.0217	0.0046	0.0340	0.0310
CH ₄	0.0015	0.0031	0.0000	0.0371	0.0542	0.0031	0.0015
N ₂ O	0.0139	0.0139	0.0062	0.0062	0.0062	0.0062	0.0139
NMHC	0.0046	0.0046	0.0015	0.0062	0.0093	0.0077	0.4365
C ₆ H ₆	0.0002	0.0002	0.0000	0.0023	0.0003	0.0077	0.0006
HCHO	0.0003	0.0003	0.0002	0.0046	0.0005	0.0033	0.0011
CH ₃ CHO	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	0.0005
CH ₂ CHCHCH ₂	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
CH ₂ CH ₂	0.0000	0.0000	n.e.	n.e.	n.e.	n.e.	n.e.
SUM	2.3452	0.3069	0.4876	0.5903	0.561	1.4518	0.728

Table A.35 Air Pollutant Emission Rates of Electricity (g/kWh)

(Delucchi, 2006)

Area	Percentage of Electricity Generation in the Area by Type									Total Air Pollution (g/kWh)
	Coal DBPCB	Coal IGCC	NG boiler	NG turbine	NG CC	Fuel-oil boiler	Bio-mass	Nuclear	Hydro, geothermal, wind, etc	
New England	15.8%	0%	8.5%	1.9%	3.9%	18.1%	1.9%	39.6%	1.03%	0.7217
Southeast	56.6%	0%	0.8%	2.1%	0%	0.3%	0.4%	33.7%	6.1%	1.3509
	Amount of Air Pollutants (g/kWh)									
	CO	NO _x	SO _x	PM	CH ₄	N ₂ O	NMHC	C ₆ H ₆	HCHO	
Sacramento	0.0134	0.2321	0.4267	0.0155	0.0007	0.0041	0.0014	0.0001	0.0001	0.6941
San Francisco	0.1950	0.2377	0.1736	0.0234	0.0150	0.0209	0.0111	0.0004	0.0009	0.6780
Los Angeles	0.0907	0.4561	0.2884	0.0283	0.0480	0.0226	0.0317	0.0009	0.0018	0.9685
San Diego	0.1263	0.2393	0.2080	0.0494	0.0859	0.0185	0.0241	0.0005	0.0010	0.7530
AVERAGE (g/kWh)										0.8610

Note: Amounts for CH₃CHO, CH₂CHCHCH₂, and CH₂CH₂ are zero.

Tables A.36 showed that the average electricity consumption rates of LRT, standard electric bus, and articulated electric bus are 2.560, 1.985, and 2.300 kWh/km. Together with the air pollution conversion rate (0.8610 g/kWh) obtained above, the default air pollutant emissions of these alternative transit systems are calculated as 2.204, 1.709, and 1.98 g/km (see Table A.33).

Table A.36 Air Pollutants of Alternative Electric Transit Systems

Systems Using Electricity	LRT	Standard Bus	Articulated Bus
Electricity Consumption (kWh/km)	2.560	1.985	2.300
Air Pollution Conversion Rate	0.8610 (g/kWh)		
Total Air Pollutants (g/km)	2.204	1.709	1.980

8. Noise

The default or reference noise (Sound Exposure Level or SEL) levels of each alternative transit system extracted from FTA (2006) are shown in Table A.34.

Table A.34 Reference Noise (SEL) of Alternative Transit Systems (FTA, 2006)

Source/Type		Conditions	dBA
LRT		At-grade	82
LRRT, AGT		Aerial, steel wheel	80
AGT or Bus on guideway		Aerial, rubber tire	78
Bus	Fuel	-	82
	Electric	Battery, roadway	80
	Hybrid (Diesel engine +Electric drive motors)	-	83

Appendix B Input Data of the DSS Demonstration

The input data of the DSS demonstration is mainly collected from the report “the Feasibility Study of the Extension Line of Damsui Rapid Transit System (the Damsui report)”. However, some of the input data needed for the DSS have to be assumed in this study because these are not provided in the Damsui report.

1. Information for the Study Area

Amounts of trips without an alternative transit system

Trips	Total (N^B)	Automobile ($N^B_{pc}+N_c$)	Motorcycle (N^B_m)	Regular bus (N^B_t)
persons/yr	246,784,165	88,151,150	50,738,650	107,894,365

Since the Damsui report did not provide the number of trips separately for peak and off-peak periods, it was assumed that 18% of the entire day’s trips take place in the peak period, based on a study by Wang (1998). The resulting number of trips in the peak and off-peak periods, without an alternative transit system are shown below.

Period	Total annual person trips (N^B)	Automobile ($N^B_{pc}+N_c$)	Motorcycle (N^B_m)	Regular bus (N^B_t)
Peak	44,421,150	15,867,207	9,132,957	19,420,986
Off-Peak	202,363,015	72,283,943	41,605,693	88,473,379

Occupancies of the existing transport modes

Since the Damsui report did not provide the occupancies of existing road transport modes, the default values which are the averages for Taipei city are used.

	Automobile	Motorcycle	Regular bus
Occupancy (persons/vehicle)	1.73	1.13	19

Average trip distance

The average trip distance for each roadway mode is one of the essential data for transport planning which can be easily obtained from the O-D information. However, this data is not presented in the Damsui report. Therefore, we assumed that the average travel distance of the study area is 10 km per trip.

Average travel time per trip (average speed)

The Damsui report did not provide the average travel time per trip or average speed. Hence, the average travel speeds in the peak and off-peak periods before the use of medium-capacity transit systems are assumed as shown below.

Average Speed (kph)	Automobile / Motorcycle	Regular Bus
Peak	13	8
Off-Peak	40	16.54

Treatment of congestion and CO₂ emission

Congestion is regarded as a cost in the Damsui report. As carbon trading is not implemented in Taiwan, *CO₂ emission* is treated as an environmental threat rather than a cost, and *Congestion* is regarded as a cost in this demonstration.

2. Attribute Importance (Weights) to the User

For the demonstration, the relative importance of the objectives (Performance, Economic Sustainability, Social Sustainability, and Environmental Sustainability) is assumed to be the same, and the relative importance of the attributes in the same objective is also assumed to be the same. In addition, the value of virtual money is regarded as equivalent to real money. These relationships for the objectives and the attributes are summarized below.

<u>Objectives:</u>						
<i>Performance, Economic Sustainability, Social Sustainability, and Environmental Sustainability</i>						
Performance	:	Economic Sustainability	:	Social Sustainability	:	Environmental Sustainability
1	:	1	:	1	:	1
<u>Performance: Line Capacity, Reliability, and System Efficiency</u>						
Line Capacity	:	Reliability	:	System Efficiency		
1	:	1	:	1		
<u>Economic Sustainability: Real Money: Costs and Revenues; Virtual Money: Congestion</u>						
\$1 Virtual Money = \$1 Real Money						
<u>Social Sustainability: Potential of Business Opportunity Increase, System Safety, and Passenger Safety</u>						
Potential of Business Opportunity Increase	:	System Safety	:	Passenger Safety		
1	:	1	:	1		
<u>Environmental Sustainability: CO₂ Emission, Air Pollution, and Noise</u>						
CO ₂ Emission	:	Air Pollution	:	Noise		
1	:	1	:	1		

3. Information of Each Line and Its Alternative Transit Systems

An optimal combination of a line and a transit alternative is to be selected from five lines and four alternative transit systems for the Damsui extension line. The guided bus system is divided into four systems based on power use as the Damsui report did not give the type of power used by these buses. Information on each line and its alternative systems from the report, default values and assumptions are given below.

3.1 Line 1: Green Mountain Line

Line	Minimum Radius	Maximum Gradient	Line Length (twice if two-way)
Information	40 m	3.50 %	19.368 km

Alternative	Vehicle	Power	ROW Category (%)			ROW Type (%)	
			A	B	C	at-grade	elevated
Do-nothing	standard bus	diesel	0	0	100	100	0
LRT	LRT	electric	52.15	47.85	0	47.85	52.15
Guided bus 1	articulated bus	diesel	52.15	47.85	0	47.85	52.15
Guided bus 2	articulated bus	CNG	52.15	47.85	0	47.85	52.15
Guided bus 3	articulated bus	LPG	52.15	47.85	0	47.85	52.15
Guided bus 4	articulated bus	electric	52.15	47.85	0	47.85	52.15
BRT	articulated bus	diesel	52.15	47.85	0	47.85	52.15

Alternative	Station Crossing (twice if two-way)		Operating Speed (km/hr)	TU Capacity (spaces/TU)	Minimum Headway (min)	Minimum Radius (m)	Maximum Gradient (%)
	no cross	cross					
Do-nothing	16	0	15 (DV)	60 (DV)	1 (DV)	10 (DV)	15 (DV)
LRT	8	8	30.77	240	2 (DV)	25	6
Guided bus 1	8	8	25.81	100	2 (DV)	13	7
Guided bus 2	8	8	25.81	100	2 (DV)	13	7
Guided bus 3	8	8	25.81	100	2 (DV)	13	7
Guided bus 4	8	8	25.81	100	2 (DV)	13	7
BRT	8	8	20 (DV)	100 (DV)	2 (DV)	13 (DV)	10 (DV)
Note: DV: default value							

Alternative	Peak hour demand (Design hourly volume, Pmax) (pax/hr)	Total annual demand (pax/year) (N_{Ai}^A)	Average travel distance (km)
Do-nothing	1650 ^a	12,000,000 ^a	5.6 ^c
LRT	2700	21,535,000	5.76
Guided bus 1	2190	16,169,500	5.44
Guided bus 2	2190	16,169,500	5.44
Guided bus 3	2190	16,169,500	5.44
Guided bus 4	2190	16,169,500	5.44
BRT	2190 ^b	16,169,500 ^b	5.44 ^b
Note: (a) The Pmax and total annual demand of the “do-nothing” alternative are assumed values, which			

generally can be obtained from an investigation for the replaced bus lines.

(b) Information for BRT is assumed to be the same as that for guided buses.

(c) Average travel distance of “do nothing” is assumed the average between LRT and guided bus.

Alternative	Total Trip (N^A)	Automobile ($N^A_{pc} + N_c$)	Motorcycle (N^A_m)	Regular bus (N^A_b)
Do-nothing	246,784,165	88,151,150	50,738,650	95,894,365 ($N^B_t - N^A_{Ai}$)
LRT	247,964,575	86,769,625	49,775,415	89,884,535
Guided bus 1	247,263,410	86,882,045	49,840,020	94,371,845
Guided bus 2	247,263,410	86,882,045	49,840,020	94,371,845
Guided bus 3	247,263,410	86,882,045	49,840,020	94,371,845
Guided bus 4	247,263,410	86,882,045	49,840,020	94,371,845
BRT *	247,263,410	86,882,045	49,840,020	94,371,845

Note: assuming the O-D distribution and modal distribution of BRT are the same as guided buses.

The Damsui report did not provide the number of peak and off-peak trips with alternative transit systems. Hence, it is again assumed that 18% of the entire day's trips are in the peak period. The resulting numbers of peak and off-peak trips as well as the assumed average speeds of each road transport mode after the use of an alternative system are shown below.

Alternative	Annual Peak Period Trips (millions)				Annual Off-peak Period Trips (millions)			
	Total	Auto	Motorcycle	RB	Total	Auto	Motorcycle	RB
Do-nothing	42.261	15.867	9.133	17.261	192.523	72.284	41.606	78.633
LRT	40.757	15.619	8.960	16.179	185.672	71.151	40.816	73.705
Guided bus 1	41.597	15.639	8.971	16.987	189.497	71.243	40.869	77.385
Guided bus 2	41.597	15.639	8.971	16.987	189.497	71.243	40.869	77.385
Guided bus 3	41.597	15.639	8.971	16.987	189.497	71.243	40.869	77.385
Guided bus 4	41.597	15.639	8.971	16.987	189.497	71.243	40.869	77.385
BRT	41.597	15.639	8.971	16.987	189.497	71.243	40.869	77.385

Average Speed (kph)	Automobile / Motorcycle		Regular Bus	
	Peak	Off-Peak	Peak	Off-Peak
Do-nothing	13	40	8	16.54
LRT	20.1	40	12	16.54
Guided bus / BRT	19.5	40	9	16.54

Alternative	Total Costs (million NT\$)			Annual Revenue (million NT\$)	Average Headway	Operating Period	Reliability ^e
	Investment	O&M	Replacement				
Do-nothing	630 ^a	802.8258	1,890 ^b	130.8 ^c	10 ^d	30 year	2.5 (DV)
LRT	8,909.04	8,065.632	4,803.56	684.537	3.5		9 (DV)
Guided bus 1	3,792.75	5,588.077	2,421.66	328.6221	2.9		7.5 (DV)
Guided bus 2	3,792.75	5,588.077	2,421.66	328.6221	2.9		7.5 (DV)
Guided bus 3	3,792.75	5,588.077	2,421.66	328.6221	2.9		7.5 (DV)
Guided bus 4	3,792.75	5,588.077	2,421.66	328.6221	2.9		7.5 (DV)
BRT ^f	3,792.75	5,588.077	2,421.66	328.6221	2.9		5 (DV)

Note: (a) Assumes only vehicle acquisition cost: number of vehicle is: [(total annual demand / occupancy) / 365 / 18] (line length/ operating speed) (1.15) = [(12,000,000 / 19) / 365 / 18] (19.368 / 15) (1.15) = 126; the cost of one regular bus is assumed at NT\$5 million.
(b) Vehicle replacement is the main replacement cost of “do-nothing”, we assumed the life of a regular bus is 8 years. Therefore, there will be three replacements in 30 years.
(c) Annual Revenue of “do-nothing” alternative is calculated by assuming an average fare is 10 NT\$ and other revenues are 9% of fare revenues.
(d) Average headway of “do-nothing” alternative is an assumed value.
(e) Reliability of alternatives is determined by default values. In addition, reliability of LRT is determined by the percentage of ROW types and default values.
(f) Assumes the costs and revenues of BRT are the same as those of a guided bus system.

Alternative	Annual Congestion (\$/year)	Business opportunity	Annual operating hours
Do-nothing	0	0	18 (hr/day)*365 = 6570 (hr/year)
LRT	802,825,800	1	
Guided bus 1	395,109,300	1	
Guided bus 2	395,109,300	1	
Guided bus 3	395,109,300	1	
Guided bus 4	395,109,300	1	
BRT	395,109,300	1	

3.2 Line 2: Blue Ocean Line – Old Street

Line	Minimum Radius	Maximum Gradient	Line Length (twice if two-way)
Information	35 m	3.70 %	16.38 km

Alternative	Vehicle	Power	ROW Category (%)			ROW Type (%)	
			A	B	C	at-grade	elevated
Do-nothing	standard bus	diesel	0	0	100	100	0
LRT	LRT	electric	3.66	87.82	8.52	96.34	3.66
Guided bus 1	articulated bus	diesel	3.66	87.82	8.52	96.34	3.66
Guided bus 2	articulated bus	CNG	3.66	87.82	8.52	96.34	3.66
Guided bus 3	articulated bus	LPG	3.66	87.82	8.52	96.34	3.66
Guided bus 4	articulated bus	electric	3.66	87.82	8.52	96.34	3.66
BRT	articulated bus	diesel	3.66	87.82	8.52	96.34	3.66

Alternative	Peak hour demand (Design hourly volume, Pmax) (pax/hr)	Total annual demand (pax/year) (N_{Ai}^A)	Average travel distance (km)
Do-nothing	1500 ^a	11,500,000 ^a	5.15 ^c
LRT	2250	20,987,500	6.24
Guided bus 1	1830	14,563,500	4.05
Guided bus 2	1830	14,563,500	4.05
Guided bus 3	1830	14,563,500	4.05
Guided bus 4	1830	14,563,500	4.05
BRT	1830 ^b	14,563,500 ^b	4.05 ^b

Note: (a) The Pmax and total annual demand are assumed values, which generally can be obtained from an investigation for the replaced bus lines.

(b) Information of BRT is assumed to be the same as that for guided bus.

(c) Average travel distance of is assumed to be the average between LRT and guided bus.

Alternative	Station Crossing (twice if two-way)		Operating Speed (km/hr)	TU Capacity (space/TU)	Technical Minimum Headway (min)	Minimum Radius (m)	Maximum Gradient (%)
	no cross	cross					
Do-nothing	20	0	15 (DV)	60 (DV)	1 (DV)	10 (DV)	15 (DV)
LRT	5	15	25.9	240	2 (DV)	25	6
Guided bus 1	5	15	22.78	100	2 (DV)	13	7
Guided bus 2	5	15	22.78	100	2 (DV)	13	7
Guided bus 3	5	15	22.78	100	2 (DV)	13	7
Guided bus 4	5	15	22.78	100	2 (DV)	13	7
BRT	5	15	20 (DV)	100 (DV)	2 (DV)	13 (DV)	10 (DV)
Note: DV: default value							

Average Speed (kph)	Automobile / Motorcycle		Regular Bus	
	Peak	Off-Peak	Peak	Off-Peak
Do-nothing	13	40	8	16.54
LRT	20.7	40	12	16.54
Guided bus / BRT	20	40	9	16.54

Alternative	Annual Peak Period Trips (millions)				Annual Off-peak Period Trips (millions)			
	Total	Auto	Motorcycle	RB	Total	Auto	Motorcycle	RB
Do-nothing	42.351	15.867	9.133	17.351	192.933	72.284	41.606	79.043
LRT	40.629	15.597	8.941	16.091	185.088	71.051	40.733	73.304
Guided bus 1	41.691	15.624	8.957	17.110	189.924	71.174	40.803	77.947
Guided bus 2	41.691	15.624	8.957	17.110	189.924	71.174	40.803	77.947
Guided bus 3	41.691	15.624	8.957	17.110	189.924	71.174	40.803	77.947
Guided bus 4	41.691	15.624	8.957	17.110	189.924	71.174	40.803	77.947
BRT	41.691	15.624	8.957	17.110	189.924	71.174	40.803	77.947

Alternative	Total Costs (million NT\$)			Annual Revenue (million NT\$)	Average Headway	Planning Period	Reliability ^e
	Investment	O&M	Replacement				
Do-nothing	515 ^a	982.3559	1,545 ^b	125.35 ^c	10 ^d	30 year	2.5 (DV)
LRT	6,942.32	6,740.416	4,288.490	565.9665	3.5		7.5 (DV)
Guided bus 1	1,934.35	4,262.681	1,821.530	283.506	2.9		7.5 (DV)
Guided bus 2	1,934.35	4,262.681	1,821.530	283.506	2.9		7.5 (DV)
Guided bus 3	1,934.35	4,262.681	1,821.530	283.506	2.9		7.5 (DV)
Guided bus 4	1,934.35	4,262.681	1,821.530	283.506	2.9		7.5 (DV)
BRT ^f	1,934.35	4,262.681	1,821.530	283.506	2.9		5 (DV)

Note: (a) Assumes only vehicle acquisition cost: number of vehicles is: [(total annual demand / occupancy) / 365 / 18] (line length/ operating speed) (1.15) = [(11,500,000 / 19) / 365 / 18] (16.38 / 15) (1.15) = 103; the cost of one regular bus is assumed to be NT\$5 million.

(b) Vehicle replacement is the main replacement cost of “do-nothing”, we assumed the life of a regular bus is 8 years. Therefore, there will be three replacements in 30 years.

(c) Annual Revenue of “do-nothing” alternative assumes an average fare is NT\$10 and other revenues are 9% of fare revenue.

(d) Average headway of “do-nothing” alternative is an assumed value.

(e) Reliability of alternatives is determined by default values. In addition, reliability of LRT is determined by the percentage of ROW types and default values.

(f) Assumes the costs and revenues of BRT are the same as those of a guided bus system.

Alternative	Annual Congestion (\$/year)	Business opportunity	Annual operating hours
Do-nothing	0	0	18 (hr/day)*365 = 6570 (hr/year)
LRT	790,375,000	1	
Guided bus 1	320,311,500	1	
Guided bus 2	320,311,500	1	
Guided bus 3	320,311,500	1	
Guided bus 4	320,311,500	1	
BRT	320,311,500	1	

3.3 Line 3: Blue Ocean Line – Tai 2 Line

Line Information	Minimum Radius	Maximum Gradient	Line Length (twice if two-way)
	35 m	3.70 %	16.418 km

Alternative	Vehicle	Power	ROW Category (%)			ROW Type (%)	
			A	B	C	at-grade	elevated
Do-nothing	standard bus	diesel	0	0	100	100	0
LRT	LRT	electric	30.76	69.24	0	69.24	30.76
Guided bus 1	articulated bus	diesel	30.76	69.24	0	69.24	30.76
Guided bus 2	articulated bus	CNG	30.76	69.24	0	69.24	30.76
Guided bus 3	articulated bus	LPG	30.76	69.24	0	69.24	30.76
Guided bus 4	articulated bus	electric	30.76	69.24	0	69.24	30.76
BRT	articulated bus	diesel	30.76	69.24	0	69.24	30.76

Alternative	Station Crossing (twice if two-way)		Operating Speed (km/hr)	TU Capacity (spaces/TU)	Minimum Headway (min)	Minimum Radius (m)	Maximum Gradient (%)
	no cross	cross					
Do-nothing	20	0	15 (DV)	60 (DV)	1 (DV)	10 (DV)	15 (DV)
LRT	12	8	25.9	240	2 (DV)	25	6
Guided bus 1	12	8	22.78	100	2 (DV)	13	7
Guided bus 2	12	8	22.78	100	2 (DV)	13	7
Guided bus 3	12	8	22.78	100	2 (DV)	13	7
Guided bus 4	12	8	22.78	100	2 (DV)	13	7
BRT	12	8	20 (DV)	100 (DV)	2 (DV)	13 (DV)	10 (DV)
Note: DV: default value							

Alternative	Peak hour demand (Design hourly volume, Pmax) (pax/hr)	Total annual demand (pax/year) (N_{Ai}^A)	Average travel distance (km)
Do-nothing	1500 ^a	11,500,000 ^a	5.15 ^c
LRT	2250	20,987,500	6.24
Guided bus 1	1830	14,563,500	4.05
Guided bus 2	1830	14,563,500	4.05
Guided bus 3	1830	14,563,500	4.05
Guided bus 4	1830	14,563,500	4.05
BRT	1830 ^b	14,563,500 ^b	4.05 ^b
<p>Note: (a) The Pmax and total annual demand are assumed values, which generally can be obtained from an investigation for the replaced bus lines.</p> <p>(b) Information for BRT is assumed to be the same as that for guided buses.</p> <p>(c) Average travel distance of “do-nothing” is assumed to be the average between LRT and guided bus.</p>			

Alternative	Annual Peak Period Trips (millions)				Annual Off-peak Period Trips (millions)			
	Total	Auto	Motorcycle	RB	Total	Auto	Motorcycle	RB
Do-nothing	42.351	15.867	9.133	17.351	192.933	72.284	41.606	79.043
LRT	40.629	15.597	8.941	16.091	185.088	71.051	40.733	73.304
Guided bus 1	41.691	15.624	8.957	17.110	189.924	71.174	40.803	77.947
Guided bus 2	41,691	15.624	8.957	17.110	189.924	71.174	40.803	77.947
Guided bus 3	41,691	15.624	8.957	17.110	189.924	71.174	40.803	77.947
Guided bus 4	41.691	15.624	8.957	17.110	189.924	71.174	40.803	77.947
BRT	41,691	15.624	8.957	17.110	189.924	71.174	40.803	77.947

Average Speed (kph)	Automobile / Motorcycle		Regular Bus	
	Peak	Off-Peak	Peak	Off-Peak
Do-nothing	13	40	8	16.54
LRT	20.7	40	12	16.54
Guided bus / BRT	20	40	9	16.54

Alternative	Total Costs (million NT\$)			Annual Revenue (million NT\$)	Average Headway	Operating Period	Reliability ^e
	Investment	O&M	Replacement				
Do-nothing	515 ^a	1,002.941	1,545 ^b	125.35 ^c	10 ^d	30 year	2.5 (DV)
LRT	8,045	6,740.314	4,739.42	575.6114	3.5		8 (DV)
Guided bus 1	3,653.47	4,240.621	1,821.57	288.8648	2.9		7.5 (DV)
Guided bus 2	3,653.47	4,240.621	1,821.57	288.8648	2.9		7.5 (DV)
Guided bus 3	3,653.47	4,240.621	1,821.57	288.8648	2.9		7.5 (DV)
Guided bus 4	3,653.47	4,240.621	1,821.57	288.8648	2.9		7.5 (DV)
BRT ^f	3,653.47	4,240.621	1,821.57	288.8648	2.9		5 (DV)

Note: (a) Assumes only vehicle acquisition cost: number of vehicle: [(total annual demand / occupancy) / 365 / 18] (line length/ operating speed) (1.15) = [(11,500,000 / 19) / 365 / 18] (16.418 / 15) (1.15) = 103; and cost of one regular bus is assumed to be NT\$5 million.

(b) Vehicle replacement is the main replacement cost of “do-nothing”, we assumed the life of a regular bus is 8 years. Therefore, there will be three replacements in 30 years.

(c) Annual Revenues of “do nothing” alternative assumes an average fare is NT\$10 and other revenues are 9% of fare revenues..

(d) Average headway of “do-nothing” alternative is an assumed value.

(e) Reliability of alternatives is determined by default values. In addition, reliability of LRT is determined by the percentage of ROW types and default values.

(f) Assumes the costs and revenues of BRT are the same as those of a guided bus system.

Alternative	Annual Congestion (\$/year)	Business opportunity	Annual operating hours
Do-nothing	0	0	18 (hr/day)*365 = 6570 (hr/year)
LRT	809,070,200	1	
Guided bus 1	335,684,500	1	
Guided bus 2	335,684,500	1	
Guided bus 3	335,684,500	1	
Guided bus 4	335,684,500	1	
BRT	335,684,500	1	

3.4 Line 4: Whole Line

Alternative	Vehicle	Power	ROW Category (%)			ROW Type (%)	
			A	B	C	at-grade	elevated
Do-nothing	standard bus	diesel	0	0	100	100	0
LRT	LRT	electric	39.03	55.58	5.39	60.97	39.03
Guided bus 1	articulated bus	diesel	39.03	55.58	5.39	60.97	39.03
Guided bus 2	articulated bus	CNG	39.03	55.58	5.39	60.97	39.03
Guided bus 3	articulated bus	LPG	39.03	55.58	5.39	60.97	39.03
Guided bus 4	articulated bus	electric	39.03	55.58	5.39	60.97	39.03
BRT	articulated bus	diesel	39.03	55.58	5.39	60.97	39.03

Line Information	Minimum Radius	Maximum Gradient	Line Length (twice if two-way)
	35 m	3.70 %	25.88 km

Alternative	Station Crossing (twice if two-way)		Operating Speed (km/hr)	TU Capacity (spaces/TU)	Minimum Headway (min)	Minimum Radius (m)	Maximum Gradient (%)
	no cross	cross					
Do-nothing	26	0	15 (DV)	60 (DV)	1 (DV)	10 (DV)	15 (DV)
LRT	11	15	28.54	240	2 (DV)	25	6
Guided bus 1	11	15	24.14	100	2 (DV)	13	7
Guided bus 2	11	15	24.14	100	2 (DV)	13	7
Guided bus 3	11	15	24.14	100	2 (DV)	13	7
Guided bus 4	11	15	24.14	100	2 (DV)	13	7
BRT	11	15	20 (DV)	100 (DV)	2 (DV)	13 (DV)	10 (DV)
Note: DV: default value							

Alternative	Peak hour demand (Design hourly volume, Pmax) (pax/hr)	Total annual demand (pax/year) (N_{Ai}^A)	Average travel distance (km)
Do-nothing	1700 ^a	15,000,000 ^a	4.59 ^c
LRT	4040	28,068,500	4.39
Guided bus 1	2050	18,213,500	4.79
Guided bus 2	2050	18,213,500	4.79
Guided bus 3	2050	18,213,500	4.79
Guided bus 4	2050	18,213,500	4.79
BRT	2050 ^b	18,213,500 ^b	4.79 ^b
<p>Note: (a) The Pmax and total annual demand of the “do-nothing” alternative are assumed values, which generally can be obtained from an investigation for the replaced bus lines.</p> <p>(b) Information of BRT is assumed the same as that for guided buses.</p> <p>(c) Average travel distance of “do-nothing” is assumed to be the average between LRT and guided bus.</p>			

Alternative	Annual Peak Period Trips (millions)				Annual Off-peak Period Trips (millions)			
	Total	Auto	Motorcycle	RB	Total	Auto	Motorcycle	RB
Do-nothing	41.721	15.867	9.133	16.721	190.063	72.284	41.606	76.173
LRT	39.608	15.563	8.898	15.147	180.437	70.899	40.536	69.002
Guided bus 1	41.079	15.544	8.887	16.648	187.136	70.812	40.486	75.839
Guided bus 2	41.079	15.544	8.887	16.648	187.136	70.812	40.486	75.839
Guided bus 3	41.079	15.544	8.887	16.648	187.136	70.812	40.486	75.839
Guided bus 4	41.079	15.544	8.887	16.648	187.136	70.812	40.486	75.839
BRT	41.079	15.544	8.887	16.648	187.136	70.812	40.486	75.839

Average Speed (kph)	Automobile / Motorcycle		Regular Bus	
	Peak	Off-Peak	Peak	Off-Peak
Do-nothing	13	40	8	16.54
LRT	21.7	40	10	16.54
Guided bus / BRT	22.2	40	8	16.54

Alternative	Annual Congestion (\$/year)	Business opportunity	Annual operating hours
Do-nothing	0	0	18 (hr/day)*365 = 6570 (hr/year)
LRT	983,616,500	1	
Guided bus 1	395,639,000	1	
Guided bus 2	395,639,000	1	
Guided bus 3	395,639,000	1	
Guided bus 4	395,639,000	1	
BRT *	395,639,000	1	

Alternative	Total Costs (million NT\$)			Annual Revenue (million NT\$)	Average Headway	Operating Period	Reliability ^e
	Investment	O&M	Replacement				
Do-nothing	1,055 ^a	1,192.583	3,165 ^b	163.5 ^c	10 ^d	30 year	2.5 (DV)
LRT	10,734.41	9,271.209	5,817.02	768.7375	3.5		8.5 (DV)
Guided bus 1	4,149.33	5,135.23	2,274.95	373.1711	2.9		7.5 (DV)
Guided bus 2	4,149.33	5,135.23	2,274.95	373.1711	2.9		7.5 (DV)
Guided bus 3	4,149.33	5,135.23	2,274.95	373.1711	2.9		7.5 (DV)
Guided bus 4	4,149.33	5,135.23	2,274.95	373.1711	2.9		7.5 (DV)
BRT ^f	4,149.33	5,135.23	2,274.95	373.1711	2.9		5 (DV)

Note: (a) Investment costs of “do-nothing” alternative assumed only vehicle acquisition cost: number of vehicle is: $[(\text{annual total demand} / \text{occupancy}) / 365 / 18] * (\text{line length} / \text{operating speed}) * (1.15)$ = $[(15,000,000 / 19) / 365 / 18] * (25.88 / 15) * (1.15) = 211$; and the cost of one regular bus is assumed NT\$5 million. Therefore, the investment cost is NT\$1,055,000,000.

(b) Vehicle replacement is the main replacement cost of “do-nothing”, we assumed the life of a regular bus is 8 years. Therefore, there will be three replacements in 30 years.

(c) Annual Revenues of “do-nothing” alternative assumes an average fare is NT\$10 and other revenues are 9% of fare revenues..

(d) Average headway of “do-nothing” alternative is an assumed value.

(e) Reliability of alternatives is determined by default values. In addition, reliability of LRT is determined by the percentage of ROW types and default values.

(f) Assumes the costs and revenues of BRT are the same as those of a guided bus systems.

3.5 Line 5: Battery Park Line

Alternative	Vehicle	Power	ROW Category (%)			ROW Type (%)	
			A	B	C	at-grade	elevated
Do-nothing	standard bus	diesel	0	0	100	100	0
LRT	LRT	electric	62.44	37.56	0	37.56	62.44
Guided bus 1	articulated bus	diesel	62.44	37.56	0	37.56	62.44
Guided bus 2	articulated bus	CNG	62.44	37.56	0	37.56	62.44
Guided bus 3	articulated bus	LPG	62.44	37.56	0	37.56	62.44
Guided bus 4	articulated bus	electric	62.44	37.56	0	37.56	62.44
BRT	articulated bus	diesel	62.44	37.56	0	37.56	62.44

Line Information	Minimum Radius	Maximum Gradient	Line Length (twice if two-way)
	60 m	5 %	14.19 km

Alternative	Station Crossing (double if two-way)		Operating Speed (km/hr)	TU Capacity (spaces/TU)	Technical Minimum Headway (min)	Minimum Radius (m)	Maximum Gradient (%)
	no cross	cross					
Do-nothing	18	0	15 (DV)	60 (DV)	1 (DV)	10 (DV)	15 (DV)
LRT	12	6	24.91	240	2 (DV)	25	6
Guided bus 1	12	6	22.92	100	2 (DV)	13	7
Guided bus 2	12	6	22.92	100	2 (DV)	13	7
Guided bus 3	12	6	22.92	100	2 (DV)	13	7
Guided bus 4	12	6	22.92	100	2 (DV)	13	7
BRT	12	6	20 (DV)	100 (DV)	2 (DV)	13 (DV)	10 (DV)
Note: DV: default value							

Alternative	Peak hour demand (Design hourly volume, Pmax) (pax/hr)	Total annual demand (pax/year) (N^A_{Ai})	Average travel distance (km)
Do-nothing	1300 ^a	9,500,000 ^a	3.85 ^c
LRT	1890	18,432,500	3.85
Guided bus 1	1610	12,796,900	3.85
Guided bus 2	1610	12,796,900	3.85
Guided bus 3	1610	12,796,900	3.85
Guided bus 4	1610	12,796,900	3.85
BRT	1610 ^b	12,796,900 ^b	3.85 ^b
<p>Note: (a) The Pmax and total annual demand of the “do-nothing” alternative are assumed values, which generally can be obtained from an investigation for the replaced bus lines.</p> <p>(b) Information on BRT is assumed to be the same as guided buses.</p> <p>(c) Average travel distance of “do-nothing” is assumed to be the average between LRT and guided bus.</p>			

Average Speed (kph)	Automobile / Motorcycle		Regular Bus	
	Peak	Off-Peak	Peak	Off-Peak
Do-nothing	13	40	8	16.54
LRT	18.5	40	10	16.54
Guided bus / BRT	18.4	40	8	16.54

Alternative	Annual Peak Period Trips (millions)				Annual Off-peak Period Trips (millions)			
	Total	Auto	Motorcycle	RB	Total	Auto	Motorcycle	RB
Do-nothing	42.711	15.867	9.133	17.711	194.573	72.284	41.606	80.683
LRT	41.089	15.676	8.970	16.443	187.185	71.412	40.865	74.909
Guided bus 1	42.002	15.678	8.971	17.354	191.345	71.420	40.869	79.056
Guided bus 2	42.002	15.678	8.971	17.354	191.345	71.420	40.869	79.056
Guided bus 3	42.002	15.678	8.971	17.354	191.345	71.420	40.869	79.056
Guided bus 4	42.002	15.678	8.971	17.354	191.345	71.420	40.869	79.056
BRT	42.002	15.678	8.971	17.354	191.345	71.420	40.869	79.056

Alternative	Annual Congestion (\$/year)	Business opportunity	Annual operating hours
Do-nothing	0	0	18 (hr/day)*365 = 6570 (hr/year)
LRT	577,415,700	1	
Guided bus 1	290,250,600	1	
Guided bus 2	290,250,600	1	
Guided bus 3	290,250,600	1	
Guided bus 4	290,250,600	1	
BRT *	290,250,600	1	

Alternative	Total Costs (million NT\$)			Annual Revenue (million NT\$)	Average Headway	Operating Period	Reliability ^e
	Investment	O&M	Replacement				
Do nothing	370 ^a	657.8633	1,110 ^b	103.55 ^c	10 ^d	30 year	2.5 (DV)
LRT	8,139.78	7,044.795	4,230.34	481.9118	3.5		9 (DV)
Guided bus 1	3,850.96	2,994.164	1,294.58	250.0377	2.9		7.5 (DV)
Guided bus 2	3,850.96	2,994.164	1,294.58	250.0377	2.9		7.5 (DV)
Guided bus 3	3,850.96	2,994.164	1,294.58	250.0377	2.9		7.5 (DV)
Guided bus 4	3,850.96	2,994.164	1,294.58	250.0377	2.9		7.5 (DV)
BRT ^f	3,850.96	2,994.164	1,294.58	250.0377	2.9		5 (DV)

Note: (a) Assumes only vehicle acquisition cost: number of vehicle is: [(annual total demand / occupancy) / 365 / 18] (line length/ operating speed) (1.15) = [(9,500,000 / 19) / 365 / 18] (14.19 / 15) (1.15) = 74; and the cost of one regular bus is assumed to be NT\$5 million.

(b) Vehicle replacement is the main replacement cost of “do-nothing”, we assumed the life of a regular bus is 8 years. Therefore, there will be three replacements in 30 years.

(c) Annual Revenue of “do-nothing” alternative assumes an average fare of NT\$10 and other revenues are 9% of fare revenues.

(d) Average headway of “do-nothing” alternative is an assumed value.

(e) Reliability of alternatives is determined by default values. In addition, reliability of LRT is determined by the percentage of ROW types and default values.

(f) Assumes the costs and revenues of BRT are the same as those of guided bus systems.