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**COMPARISON OF LEVEL OF SERVICE
AND COST-EFFECTIVENESS OF
TRANSITWAY AND LIGHT RAIL TRANSIT (LRT)-BASED SYSTEMS**

by

**MOHAMMAD NISAR, B.Sc. (Civil Engineering)
University of Peshawar, 1979**

**A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of**

(Master of Engineering)

Department of Civil Engineering

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December 1989
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**The undersigned recommend to the Faculty of Graduate Studies
and Research acceptance of the thesis**

**"Comparison of Level of Service
and Cost-Effectiveness of
Transitway and Light Rail Transit (LRT)-Based Systems"**

**submitted by Mohammad Nisar, B.Sc. (Civil Engineering)
in partial fulfilment of the requirements for
the degree of Master of Engineering**

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December 1989**

ABSTRACT

A methodological framework for economic and service assessment is developed. Urban transit system (Transitway and LRT) is then defined in detail in terms of its infrastructure components, vehicles, operational methods and capacities.

Door-to-door travel time for urban commuters is assessed in terms of ride time and non-ride time based on various Level of Service (LOS) parameters. The average speed of a rapid transit system on a full urban area-wide basis is determined for both Transitway and LRT systems.

Life cycle costs are developed per passenger-kilometre and per passenger, based on costing models and computation procedures developed in the thesis. Numerous sensitivity tests are carried out to assess the capability of each individual system.

Cost-effectiveness comparisons are made both theoretically and empirically. Comparison is made to demonstrate the resulting cost-effectiveness of both systems.

Implementation issues and the staging flexibility of Transitway and LRT system are described.

Recommendations are made to give serious consideration to the Transitway alternative where rapid transit alternative evaluations are carried for low to medium-sized urban areas. Also, the need of further study is recommended to include users, builders and operators points of view in the evaluation process.

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LIST OF SYMBOLS

SYMBOL	DESCRIPTION
a	Acceleration (meter per second per second)
ann	Annual
Articulated Bus	60 feet (18 meters)
ALRT	Advanced Light Rail Transit
CBD	Central Business District
CT	Calgary Transit
d	Deceleration (meter per second per second)
HCM	Highway Capacity Manual (1985)
HOV	High Occupancy Vehicle
km	Kilometre
km/h	Kilometres per hour
LRT	Light Rail Transit
LRV	Light Rail Vehicle
LOS	Level Of Service
m/min	Meters per minute
NCHRP	National Cooperative Highway Research Program
North America	Canada and United States only included
Pass	Passenger
Pass-km	Passenger-kilometres

PK-Veh	Peak Schedule Vehicle
RRT	Rail Rapid Transit
RMOC	Regional Municipality of Ottawa-Carleton
ROW	Right Of Way
sec	Second
Standard Bus	40 feet (12 meters)

CHAPTER 1

INTRODUCTION

1.1 Background

Many urban transit authorities are struggling to maintain their existing ridership rather than increase their market. Reasons include the continuous increase in automobile ownership and the shift in the structure of cities, for example, increased suburbanization (1,2,3,4).

The search for a cost-effective and efficient urban transit system is a continuous process. The history of expenditures and the recent decline in urban transit performance indicates that spending large sums of money on transit infrastructure is not the sole solution. Option selection in North America is not based solely on technical grounds. The plan selection process in North America is more socio-technical in nature. Much weight is given to the political process including public participation. In these circumstances, to select an option the planner must convince the decision makers of its merits. The politicians then have to convince the public of the plan's merits. Decisions made about light rail transit (LRT) and Transitways are generally the results of these circumstances. In contrast, the European practice and the World Bank guidelines tend to base decisions on detailed cost-benefit criteria (5).

Very few urban transit systems operate with only one mode. In North America, only small cities without rapid transit use only one type of technology. The

Ottawa-Carleton Region is an exception. The complete transit system is based on motor bus technology. Other medium-and-large sized cities use various public transit technologies to provide service to the entire urban area. These technologies include motor bus, LRT, advanced light rail transit system (ALRT) and rail rapid transit (RRT).

The major public transportation systems are: the surface bus transit system, rail rapid transit system and the intermediate capacity transit systems. Examples of intermediate transit systems include Transitways, LRT and ALRT. Literature is agreed upon that surface bus transit system is preferred for small size and low density urban areas where hourly passenger volumes are about 2,000 to 7,000. These hourly passenger volumes can increase up to 10,000 with the use of bus only lanes and other priority measures. This type of system is available with lower capital expenditures but higher operating costs. Rail rapid transit is preferred for high density urbanized areas and high density corridors where minimal hourly passenger volumes of about 40,000 or more are generated. The capital intensive nature of this system can be offset with low operating costs dependent on actual passenger volumes. The LRT, ALRT and Transitway systems fall in between the two systems mentioned above. They are preferable for areas with hourly volumes of 10,000 to 30,000 (depending on the size and density of the urbanized area). These systems are also moderate in terms of capital expenditure and operating costs.

The passenger volumes mentioned above for the last two types of systems are not evenly distributed over the entire urban area. A few specific corridors usually leading to the Central Business District (CBD) are used heavily compared to the rest

of the area. At these locations it is necessary to provide an exclusive right of way (ROW) for public transit vehicles to increase their speed and reduce traffic congestion on existing roads.

A typical urban transit system has four parts: the main line haul portion (usually an exclusive facility), terminal stations and the access/egress arrangements at both ends of the line haul facility. The access feeds the main line haul portion; the egress distributes traffic as part of the system. The access/egress system usually consists of feeder buses, park-and-ride, kiss-and-ride and walk.

Where many options are available (e.g., Transitway, LRT and ALRT), transit professionals disagree about which one works best in a medium-sized urban area.

In the 1960s and 1970s, a series of studies demonstrated the merits of the bus rapid transit systems. These studies highlighted the cost superiority and higher level of service (LOS) of the bus rapid transit over its competitors.

In the early 1960s, Meyer, Kain and Whol (6) did an extensive study of transit systems. They compared the standard bus with heavy rail transit (up to 10 cars per train) for both low and high density urban areas. They highlighted the merits of bus rapid transit for low to medium density urban areas. This study was followed by another investigation by Deen and James in 1969 (7). Examining the relative costs of bus and rail rapid transit led them to the conclusion of the cost advantages of bus rapid transit system. They showed the various operational methods for using the motor bus technology, taking into account its operational flexibility. They also included the articulated bus in their analysis. In 1973, Boyd et al. (8) reinforced these findings. Wilbur Smith and Associates (9) took a closer look at the bus rapid

transit system in densely populated areas, CBD cores, in 1975. They identified various options and technologies and estimated costs. Bus rapid transit, both on-street and off-street, tunnelling and associated ventilation were thoroughly studied. They did not, however, include the operation of express buses on expressways because they felt that it was already well-documented. The economic studies were enhanced by other research showing the potential of the bus rapid transit system (10,11,12).

In spite of these intensive studies, until recently practically no attention was paid to the bus rapid transit system. In the 1970s and even in the 1980s, numerous cities in North America opted for LRT-based systems. Because LRT system is capital intensive, very few cities build tracks in more than one corridor. For the rest of their urbanized area, they rely on feeder buses. To increase the ridership of their rapid transit system, huge expenditures were made or have been committed for the automation of buses and other priority measures, including express buses and contra or concurrent flow lanes. Other measures include free transfers or timed-transfers, free rides for the elderly or even free rides for every one in the CBD areas (13).

The Washington, D.C. Shirley (I-395) Transitway carries, in one peak hour, about 17,000 one-way passengers travelling in vans, carpools and buses. This compares to the 14,000 passengers of Chicago's Dan Ryan Line — the busiest RRT line in the transit area. The (I-66) portion of the Shirley Transitway carries 100,000 daily passengers — about 2.5 times more than the Washington metro rail extension. This extension is of the same length, located in a parallel corridor but cost 1.2 times more than the (I-66) portion of the Shirley Transitway in terms of capital expendi-

tures (14). Similarly Katy Transitways (I-10) and (I-45) of Houston, Texas carries 16,000 and 4,000 one-way peak hour passengers respectively. Elmonte (I-10) Transitway of Los Angeles, California serves 43,000 daily passengers and a 54,000 daily passenger demand has been forecasted for the Long Beach LRT system (15,16). The Pittsburgh Busway carries 1.31 times more passenger on the average day than the Pittsburgh LRT system with one third the capital and operating costs (17). The Ottawa-Carleton West Transitway of 12.7 km length carries 9,000 peak hour passengers. This compares with the Calgary LRT system that is 28.6 km in length and carries 6,300 peak hour passengers (13,15). Both these Transitways are limited in nature, however, they still, compare with well-established rapid transit systems.

Rail rapid transit, which helps create skyscrapers around its stations and opportunities for employment, is able to attract less than 4% of these employees that work in that area (2). The main reason for this problem is probably the route-specific technological character — the vehicle cannot go where the commuter wants to go. On the other hand, according to a survey conducted by the OC Transpo, the Ottawa-Carleton Transitway is used by about 30% of the employees working in employment centres surrounding the stations because they get a door-to-door one-seat ride (18).

The recent decline of rail rapid transit, the rapid growth in suburbanization and the recently successful experience of the Transitways have attracted the attention of transportation planners seeking the merits of motor bus technology (1,2,3,16).

Urban planners, who are concerned with the sudden increase of population and congestion in the suburbs, are viewing Transitways with a lot of interest because

of perceived cost-effectiveness and the operational flexibility that helps relieve congestion (1,2,3).

1.2 Research Objectives

This study will compare the LOS and cost-effectiveness of Transitways and LRT-based systems. A relative comparison of LOS and economic factors will fill the gap of information required for defining, analyzing and evaluating public transit alternatives for medium-sized urban areas. The main objectives are:

1. to assess the LOS for both Transitways and LRT-based systems;
2. to study the role of Transitways and LRT-based systems within the spectrum of public rapid transportation;
3. to investigate the relative cost-efficiency of Transitways versus LRT-based systems;
4. to investigate the relative cost-effectiveness of Transitways and LRT-based systems; and
5. to identify the conditions that are conducive to consideration of either Transitways or LRT-based systems for implementation.

1.3 Scope

The scope of this research is limited to Transitways and LRT-based systems. The analysis does not extend beyond medium-sized urban areas. It does not include intermediate capacity rail rapid transit system such as the ALRT, which is driverless and highly automated. Both standard and articulated buses, are however, included

in the analysis.

The LOS, cost-efficiency and cost-effectiveness information developed in this research is an original contribution to the knowledge base in urban transportation. Qualitative assessments have been recently reported in the literature, but this research attempts to go beyond currently available answers on many key factors including, LOS, cost and the effectiveness of rapid transit system alternatives for medium density corridors.

1.4 Research Approach

1.4.1 Overview

Based on a literature review of many systems and reading ideas of both proponents and opponents of each system, an investigation of various factors affecting the operations and economics of each system was deemed to be necessary.

An economic and level of service framework is adopted from Reference (19) which was formulated to assess the cost-efficiency and cost-effectiveness of the system under consideration. The framework is shown in Figure 1.1. This research focuses on the factors included in the part of the framework marked by the dotted-line. Population and socio-economic projections, modal split estimates and revenue calculations are not included in this research. The discussion provided in this section is intended as background information.

Basic costing data obtained from the Regional Municipality of Ottawa-Carleton (RMOC) and Calgary Transit (CT) are used as a starting point in the framework for comparative analysis. Some sensitivity tests have been run to

Figure 1.1: Methodological Framework for Economic and Service Assessment

Source: Reference 19

judge the capability of the systems.

1.4.2. Rationale for the Research Approach

Planning for public transit system requires systematic detailed study. The necessary factors for consideration are:

- a) population of the urban area;
- b) employment in the area;
- c) jobs and population locations;
- d) socio-economic characteristics of the inhabitants;
- e) users' ability and willingness to pay transportation charges;
- f) the financial capability of the operator;
- g) forecast of the transit usage;
- h) the expected revenue;
- i) the staging ability of the system in terms of building and operating the system;
- k) the staging of capacity; and
- i) the existing and future transit modal split targets.

The systems under consideration must be defined in detail in terms of each system's components, the capacity of each component, capital costs, operating costs, maintenance costs, LOS and cost effectiveness. A range of sensitivity tests are needed to show the capability of the system under future uncertainties.

Population and Socio-Economic Projections

Transportation is a derived demand. Travel is related to a specific purpose or interrelated purposes. Urban transit is used heavily for work trips. Increasing population coupled with employment increases result in urban travel growth. Urban transit demand is also related to city population, employment and the corresponding land uses. The use of urban transit is also affected by other socio-economic characteristics of the urban community. The cost, LOS and disincentives to automobile use (e.g., parking constraints) also influence transit demand.

Population forecasting and determining the socio-economic characteristics of an urban area are uncertain tasks in the urban transportation process. A forecast from 44 transportation planning studies in Great Britain was compared with actual observed values. A 10% average forecasting error was found in population estimates, 35% error margin in public transport trips, 13% error in screen-line volume estimates and 20% in household estimates (20). In the United States the ridership forecast for Baltimore fell below the actual travel level by 50%, in Portland by 45% and in Miami the actual ridership is only 12% of the forecasted value (16). Inaccuracy in forecasting trips per capita is offset by the rapid increase in population. For example, in developing countries, the average urban population increased by 50% or more in one decade (21). In the same period, 21 metropolitan areas of the United States showed a decline of 4% to 28% in central city population (22). Forecasting inaccuracy directly affects the supply and usage of transit. In Canada, population increase is more modest than in developing countries and the differential population growth in suburbs compared to central urban areas further complicates the process of matching demand to supply of urban transit. A study of 13 cities in Great Britain

and Germany showed an increase in suburban population and a decrease in CBD population. Similar surveys are also available for North American cities (4,22,23).

A recent survey of 120 metropolitan areas in the United States showed a decline in mass transit use. This is due to migration of people to smaller cities or the suburbs (23). The shift to suburbanization is the result of lower rents, telecommunications, parking, room to expand and proximity to labour market.

These surveys emphasize that rapid transit, which once mainly provided for the CBD-oriented trips, is now needed for suburban areas. Now the number of these trips outnumbers the suburb-to-CBD trips. Transit usage increases with its availability. Some planners are asking for a revision of the CBD trip attraction criterion (24). Fully developed systems carry a high percentage of trips, for example 32.85% in Toronto compared to 3.7% for the rest of the country. In Toronto about 80% of commuters have access to the transit system compared to 25% for the rest of the country (25).

Automobile ownership also affects transit usage. As automobile ownership decreases (from North America to Europe and further to developing countries) transit usage increases. The relationship between city population, automobile ownership and transit usage is shown in Figures 1.2 and 1.3. Figure 1.2 shows the relationship between automobile ownership per 1,000 people and the share of public transit in the urban travel market. The relationship between city population and the market share of public transit is shown in Figure 1.3.

The financial constraints of the operator and uncertain future, the staging of urban transit supply at various population levels, may give the opportunity to verify

Figure 1.2: The Impact of Auto Ownership on Urban Transit Usage

Source: References 21,26,27

Figure 1.3: The Impact of City Population on Urban Transit Usage

Source: References 21,26,27

the various resulting consequences.

Modal Split Targets

When population and employment estimates are complete and the future projections are made, then the modal split targets can be estimated. These modal split targets estimate the percentage of trips by each available mode. Urban Transportation Models are used to estimate trip interchanges and modal splits.

Trip interchange models include service characteristics such as travel time, costs, trip productions and attractions. The trip end models account for automobile ownership, income, the population density of each zone and the number of persons in each household among many other factors or parameters (20). Both models are based on aggregation of data for various zones which give less accurate results. For modal split estimates, models based on disaggregate choice concepts (e.g., Multinomial Logit Model) are used.

Estimated targets can be compared with the actual splits obtained by screen-lines, various employment and origin-destination surveys. The comparison of the estimated and actual targets plays an important role in decision-making about future expenditures and expansion.

Population and employment projections and their location, modal split estimates and future targets are the best measures for selection and evaluation of transit alternatives.

1.5 Thesis Organization

The thesis is organized in the following manner.

Chapter 2 explains the various characteristics of both the Transitway and LRT systems. Numerous types and operational methods of both systems are also discussed.

Capacity of the infrastructure and vehicles and vehicle performance, are dealt with in Chapter 3. The components of the urban transit system and other factors affecting the capacity of these systems are also explained here.

In Chapter 4, the typical urban trip is explained in detail and the various impacts of Transitway service upon the urban trip are demonstrated. A level of service simulation model is developed for both the Transitway and LRT systems. The average weighted speed for the entire urban area is assessed here.

In Chapter 5, yearly costs are estimated for different passenger volumes. Some sensitivity tests are run to see the effectiveness of the systems under consideration.

Cost-effectiveness of the systems is described both theoretically and analytically in Chapter 6.

Chapter 7 deals with the implementation process staging issues. It is shown here that the Transitway option is more flexible both in terms of construction and operation than LRT system.

Conclusions and recommendations are presented in Chapter 8.

CHAPTER 2

CHARACTERISTICS OF TRANSITWAY AND LRT SYSTEMS

2.1 Transitways

Transitways, also known as busways, are a relatively new concept and alternative to conventional urban transportation options. A Transitway is an exclusive roadway or designated lane of a freeway or arterial lane for the exclusive use of buses and/or other high occupancy vehicles (HOV).

2.1.1 Types of Transitways

There are four types of Transitways.

- Type 1: A roadway or a lane of a roadway built in a separate ROW that is used exclusively by buses and HOVs. The Ottawa-Carleton Transitway and East and South busways of Pittsburgh are examples of this type. This facility provides high speed travel and high capacity. In Ottawa and Pittsburgh, the HOVs are not used in these facilities because of high passenger demand for transit service.
- Type 2: A roadway that is physically separated from other traffic but built within the freeway ROW and is designated for the use of buses and/or HOVs. These Transitways are in operation in Houston, Washington, D.C. and Los Angeles.

Type 3: A freeway or arterial lane with no physical separation from other traffic and designated for the exclusive use of buses and HOVs in the peak direction of flow. It is also called concurrent flow, with flow or normal flow lane. Often this type of Transitway is used only during peak periods of operation.

Type 4: A freeway or arterial lane taken from the off-peak direction and designated for the use of the buses and/or HOV, travelling in the peak direction. Other names such as contra flow lane, reverse flow lane or wrong way lane have been given to this type of Transitway.

Types 3 and 4 are most widely used in the CBD or other congested corridors of the city. The Highway Capacity Manual (HCM 1985) indicates more than 23 locations in North America alone where concurrent or contra flow lanes are in operation (28). About 150 to 180 buses/hour carrying 10,000 or more passengers have been recorded in Ottawa and elsewhere using these Transitways (28,29).

The major North American Transitways are shown in Table 2.1. This table does not include concurrent or contra flow lanes. Other successful Transitways in operation are in Essen (West Germany), Adelaide (Australia), Hong Kong, England and Brazil (15).

2.2 Operation of Services

A Transitway allows motor bus technology to deliver services in a variety of ways. This operational flexibility enables route and schedule changes and adoption of numerous types of operation.

Table 2.1: Major North American Transitways

Major North American Exclusive Busways

Facility/City	Year of Implementation	Length (km)	Passengers Served
Exclusive facility on separate right of way			
- Ottawa-Carleton			
West Transitway	1983	12.7	9,000 peak hr. 115,000 daily
East Transitway	1983	7.4	9,000 peak hr. 95,000 daily
- Pittsburgh, PA			
East Busway	1983	11.0	5,590 peak 28,500 daily
South Busway	1977	5.6	2,950 peak 18,000 daily
Exclusive facility on Freeway right of way			
- Houston, Texas			
I-10 (Katy)	1984	18.5 (one way)	4,114 peak hr. 15,900 daily
I-45 (North)	1979	15.5 (one way)	4,055 peak hr. 14,000 daily
- Los Angeles, CA			
I-10 (El Monte)	1973	17.7	8,000 peak hr. 43,000 daily
- Washington, D.C.			
I-395 Shirley	1969	17.7 (one way)	17,260 peak hr. 63,486 daily
I-66	1982	15.5 (one way)	11,260 peak hr. 31,720 daily

Source: Reference 15

Previous studies have shown many ways of providing door-to-door service on bus rapid transit system by using Transitways (7,10). The few most appropriate configurations are shown in Figure 2.1.

2.2.1 Methods of Operation

Four types of services are shown in Figure 2.1. The first one is similar to the rail rapid transit system. The buses stop at each station. If no service is offered beyond the exclusive facility, then special buses can be manufactured with extra wide doors and longer than the standard ones. The design of these buses could be adapted to use a higher platform. This will reduce the station stop time. Fare collection can also be taken off the buses (7). Service similar to rail transit is provided, but higher frequencies of bus departure are available to passengers. This offers reduced waiting time at stations. Passengers have access to the stations by walking, park-and-ride, kiss-and-ride or feeder bus service.

A second service is the direct express service. This is comprised of a local feeder and a line haul service without any transfer. This type of service provides a "one-seat" ride from origin to destination. The majority of passengers escape the trouble of transfers and waiting at the station for connecting service. Because service is express, it does not stop at every station. This means a high level of service is provided to the through passengers. The frequency of service at some stations of the Transitway is also increased.

A third service is the area-wide service. It uses the Transitway as part of the entire route. By using the exclusive facility the overall speed is enhanced and

Figure 2.1: Transitway Services

Source: Reference 19

frequency of service at Transitway stations is increased. With this type of service a wider area is covered. This increases ridership and reduces the feeder services (if provided separately).

A fourth type of service is the local feeder service. This service gives access to Transitway stations. Passengers who work in the buildings containing the station or in surrounding land uses, benefit from this service. Passengers who transfer to the Transitway can also use this service.

Individual services of the Transitway are explained above. If needed, all these services can operate at the same time. In the Ottawa-Carleton case, many services are provided this way, as shown in Figure 2.2. It is interesting that the same facility is used by overlapping types of services and routes. This is the main advantage of Transitway over LRT system. The two-track facility of LRT system cannot be used by more than one service at a time. If any other secondary service needs to be operated, a third track is necessary. This is costly and practically non-existent at this time.

2.3 Light Rail Transit System

The LRT system considered here is the one which uses exclusive ROW in the outlying areas and surface street or subway operation in the CBD area. The disadvantage of the CBD surface operation limits the ability to use higher platforms. Also, LRT system can be operated with coupled vehicles and off-the-vehicle fare collection. As the light rail vehicle (LRV) cannot be operated off the track, its major service is between stations. The services provided by the LRT-based system are

BUSWAY OPERATION

Figure 2.2: Ottawa-Carleton Rapid Transit Operations

Source: Reference 30

shown in Figure 2.3.

2.3.1 Methods of Operation

As shown in Figure 2.3, two types of services are provided by the LRT-based system.

The first service is provided between stations. The vehicles operate on a fixed exclusive track, so wider doors or doors on both sides and trains of coupled vehicles can be used. Longer trains can be operated if station platform length permits. An LRT-based system provides a comfortable ride for all passengers. But a high LOS is provided only for those passengers whose origin and destination are within walking distance. Park-and-ride and kiss-and-ride facilities, however, can be enjoyed only at one end of the journey.

Area-wide direct service is not possible with the LRT option, so the technology is mainly suitable for specific high density corridors. Passengers with convenient access to stations (e.g., within walking distance) will benefit considerably.

The second service requires feeder buses. The services of the LRT system, feeder bus or intermodal transfer can be connected with this service. Since the walking capability of a person is limited, the majority of passengers of LRT systems require transfers from other vehicles. The walking ability of passengers and the off-track operational inability of the LRV have actually led to the introduction of formation of focal-transfer points and free transfer or timed-transfer solutions. For example, in the case of Edmonton's LRT system, about 90% of the riders use feeder

buses for at least one end of their journey (31). The Edmonton LRT and various connecting services and transfer focal points are shown in Figure 2.4.

2.4 Comparative Features

Transitway and LRT systems have comparable features. Some of these comparative features are shown in Table 2.2. As shown in this table, the Transitway service can be provided with the use of exclusive facility. Service in mixed traffic and designated lanes can be used as a part of the route. The LRT system is route specific. Because most buses use the exclusive facility as a part of the entire route, stations with higher platforms are restricted. In the case of LRT system technology adopts to suit higher platforms dependent on the CBD service. The motor bus technology is controlled manually and has a long successful experience. LRT technology is controlled with the use of signals. Buses are available in different sizes (medium, standard and articulated) and can be used according to needs. LRVs are available in longer and wider sizes but before the construction of the track, the decision about vehicle type has to be made. Additionally, LRV is operated with electric traction which contributes little air pollution but buses are generally diesel-operated.

2.5 The Choice

Comparative features of both systems, the transit demands of the area and the respective origin and destination of the commuters must be considered before a decision is reached. Transitways, which can be implemented in a short period of

Figure 2.4: Edmonton Transit System Network and Focal Points

Source: Reference 25

Table 2.2: Comparative Features of Transitway and LRT System

Item	Transitway	LRT
Guideway	Roadway -Exclusive -Mixed Traffic -Designated Lane	Rail Track -Exclusive
Station	Off-Line On-Line Low Platform	Off-Line (Subway) On-Line Low Platform High Platform
Control	Manual	With Signals
Vehicles	Smaller to Larger	Larger
Fuel	Diesel (at present) Alternative fuels (future)	Electric

time with modest initial costs, have other attractive attributes. These attributes include the ease of matching supply with demand, securing the ROW in the early stages of the construction and the offer of more frequent service. The LRT system has higher initial costs, requires a longer implementation period and offers infrequent service. On the other hand, LRT systems do provide comfortable rides and wider vehicles. These are also relevant considerations in the choice of public rapid transit.

CHAPTER 3

CAPACITY OF TRANSITWAY AND LRT SYSTEMS

3.1 Overview

The concept of capacity of urban rapid transit systems is different from the highway concept. With highway capacity, concern lies mainly with the safe physical accommodation of vehicles on specified segments for specified periods of time under prevailing conditions. With rapid transit, capacity is based on safe physical accommodation of vehicles (in controlled conditions) on a segment of lane/track. The capacity concept also incorporates the occupancy of vehicles. The capacity of a rapid transit system has been well explained by previous authors (25,32,33).

Humans are different than "goods" because they cannot be physically dumped into vehicles. Certain guidelines must be followed while transporting them from one place to another. They have a limited tolerance of crowds and long periods of standing in one spot or in moving vehicles. They seek comfort and safety when travelling, boarding on or alighting from a vehicle. Therefore, the comfort, safety and other human travel-related behaviours must be considered in the analysis of transit capacity.

The total capacity of a rapid transit system also depends on the number of lanes/tracks. The more passengers carried in a specified direction during a given time period, the higher number of lanes/tracks that are needed for safe and efficient operation. This is constrained by the capacity of other components of the system,

such as access/egress systems, stations, vehicle or train length, operating frequencies and other relevant factors.

3.2 Components of a Rapid Transit System

3.2.1 Overview

A typical rapid transit system consists of four sub-systems as defined in Chapter 1. These are: access (i.e., collection), terminal, line haul and egress (i.e., distribution). These are shown in Figure 3.1.

The access system's main purpose is to enhance access to the line haul facility through a terminal. The passengers have access to the system by feeder buses, park-and-ride, kiss-and-ride and walk.

The line haul facility in conjunction with the terminal consists of main collector and distributor stations, rail tracks or roadway in exclusive ROW along with other stations for loading and unloading passengers.

The egress system is the same as the access system. These components are explained in the following sections.

3.2.2 Access/Egress

Access/egress systems consist of feeder buses, park-and-ride, kiss-and-ride and walk. They usually operate in mixed traffic. No separate ROW is provided for these services because of their diversified nature in terms of routes numbers, routes lengths and their capacity.

Passengers who walk to the station usually use the walkways that are

Figure 3.1: Typical Urban Transit System

connected to the station for this purpose. Other general public pathways can also be used by passengers. In Ottawa-Carleton, passengers who walk longer than 400 metres are provided with paved walkways. The basic reasons include comfort and an effort to make the system more attractive to potential users (53).

Park-and-ride facilities at rapid transit stations need extra space for construction and involve extra costs. This facility is usually provided at outlying stations. To attract more passengers, free parking is generally provided. Feeder buses also involve extra costs for various operating facilities at the rapid transit station (e.g., turnaround facility for buses, loading and unloading platforms and garages).

3.2.3 Access/Egress To or From Station Platform

The pedestrian corridors, stairs and escalators link to the station platform where the loading and unloading of passengers occurs. The number of stairs and escalators and their dimensions, along with the width of the walkway corridors, are based on passenger volumes. The geometry of these items normally take human factors into account. The design of walkways, stairs, escalators and their corresponding capacities have been extensively studied by many authors. Capacity and LOS guidelines are discussed in References (5,28).

3.2.4 Stations

Rapid transit stations can be categorised in two ways: According to layout they are central and side platform stations and operationally they are on-line and off-line

stations.

Central platform stations occupy little space compared to side platform stations because the same platform can be used for both-way operation. When the system needs expansion, the side platform type station can be expanded horizontally and the central platform type stations can be expanded vertically. A station will need more space (especially with rail transit) if turnaround facilities are provided. If space is limited (e.g., CBD locations), the stations are built underground. The length of the station platform is based on the number of buses to be accommodated at a time or the length of the train.

The overall size of a station is governed by the number of passengers and the operation-related utilities. The on-line station is provided where each bus or train must stop and the off-line station provides non-stop services. When the station becomes bigger and the corresponding activities increase, the capacity extends and capital and operating costs rise.

Calgary's LRT system stations are composed of central and side platform types and presently accommodate 3-car trains. These can extend to 5-car trains in the future (13). The Ottawa-Carleton Transitway has side platform stations. Given the off-line design, the Ottawa-Carleton Transitway stations are larger and costlier than Calgary's LRT stations.

3.2.5 Transit Vehicles

Transit vehicles are the most important part of the system. Vehicles operate as single units (motor bus technology) and multiple units (rail system). The size,

especially the exterior dimensions and weight of the vehicles, depends on the geometry of the guideway. The type and size, especially the interior dimensions, are dictated by passenger volumes to be served and the comfort level provided to the passengers. The seat arrangements and amount of space allocated to standees also depends on the interior dimensions of the vehicle. The selection of vehicles is also based on the operating performance characteristics. The visual appearance of the transit vehicle also serves an important purpose (i.e., to attract passengers).

The interior of the vehicle is divided into two parts. The first is used by passengers (i.e., usable area) and the second consists of non-usable areas such as space occupied by the console, doors, stairs and stair cases.

Buses are available in various sizes, including mini, small, standard and articulated. LRVs are available in single and articulated units. Due to problems with turnaround activity (e.g., more space, extra costs, longer time), articulated LRVs have two consoles — one at each end. An extra console reduces the usable space that could otherwise be used by passengers.

3.2.6 Line Haul

The roadway for buses and rail track for trains, which connect the collection and distribution portions of the urban transit system, are called the line haul. This portion of the urban transit is also called rapid transit. To carry more passengers and provide a higher LOS, a two-way guideway is necessary. In the case of LRT system, one track can be used only in one direction at a time since the stations are on-line. This exclusive facility is usually grade separated, on, above or below the

ground. The geometry and facility type varies depending on the specific needs of the urban area (e.g., topography of the selected route, the effect of noise on the neighbourhood).

The Ottawa-Carleton Transitway and Calgary's LRT system (excluding CBD portion) are two-way exclusive facilities. Both are grade separated and constructed on the surface. In the case of Ottawa-Carleton, at some locations, the Transitway is constructed in a U-shape ditch to lessen the noise impact on the neighbourhoods. Calgary's LRT system is designed to have a small portion of elevated guideways (bridges) for crossing some roads and waterways. One segment is underground because there is no available ROW on the surface (13). For both Ottawa and Calgary, the CBD area operation is carried on at street level with partial restrictions on other traffic.

3.3 Rapid Transit Capacity Analysis

3.3.1 Overview

The components of a rapid transit system play an important role in capacity analysis. In analyzing rapid transit capacity all these factors must be taken into account.

The hourly capacity of a single lane/track of a rapid transit is determined by the number of vehicles or trains that can pass a given point during one hour. This includes the number of passengers carried in each vehicle or train (25,32). Using this definition of transit capacity concludes that the capacity of a transit lane/track is directly proportional to the length of the vehicle or train and is inversely proportional

to the headway between two vehicles or trains. This implies that capacity increases by increasing the dimensions of individual vehicles or the length of the train. Capacity can also be increased by minimizing headway between vehicles or trains. This can, however, create problems such as lengthening the train and minimizing headways implies an increase in the number of vehicles and other equipment. This will increase the total cost of the system. Operating longer trains means more infrequent service and a degradation of the level of service.

Concerning the reduction of the number of vehicles, a study of basic factors and a search of literature suggests increasing the speed of the vehicle or train as a solution. Speed can be increased in two ways. One is the provision of exclusive ROW — at extra cost. The other is a non-stop service between the origin and destination. A non-stop service in the urban environment rarely exists. A partial solution is wider station spacing but building stations further apart means a reduction in patronage. This reduction will increase the operating costs per passenger due to less revenue. In North America the majority of the exclusive facilities (both Transitway and LRT systems) provide station spacing of less than one kilometre in order to not lose the potential patronage (35,36).

It is clear that the urban transit capacity is dependent upon many factors. One component of the system influences the other and vice versa. Maximizing the performance or capacity of one component increases or decreases the capacity of the other component.

3.3.2 Access/Egress

The access/egress systems collect and distribute passengers from various urban locations and concentrate them on a specified rapid transit station. They include feeder buses, park-and-ride, kiss-and-ride and walk. Depending on the location of the station and the desired or predicted number of passengers, the line haul facility dictates the frequency of feeder buses. For rail rapid transit, more than 90% of the passengers start their journey at home-end by feeder bus or automobile (5). In Edmonton's LRT system, 90% of the passengers use feeder bus at the home-end (31). Walk and automobile (access) modes are used by only 10% of the total number of public transit users in Edmonton. With Transitway, these 90% passengers can be served without transfer while with LRT system, they have to transfer to LRT system at rapid transit station.

3.3.3 Station Capacity

Station capacity is the ability to process or serve the number of passengers per unit of time. The main processor at the station is the platform for loading and unloading passengers. The number of vehicles or train length needed to serve a certain amount of passengers and platform dimensions (i.e., length and width) are the main factors governing this capacity.

Other processors are also of interest. Capacity of walking corridors is discussed in the Highway Capacity Manual (28). For stairs and escalators the reader should refer to Fruin (5,37). For rapid transit, the capacity of walkways, stairs and escalators are in balance with the capacity of the station platform.

Humans occupy space when walking and need a certain amount ROW for

ease of movement. When the concentration of people increases at a specific location, free movement becomes restricted. This reduces walking speed and throughput. The capacity of the walkway is more than stairs and escalators. This is due to the restricted rise and tread arrangements and humans climbing efforts that reduce walking speed and thus the throughput of the processor. Humans use 10 to 15 times more energy climbing stairs than required for equal horizontal level distances. In contrast, this energy consumption reduces to 3 times when descending stairs (5).

Reduced capacity of stairs and escalators sometimes causes a congestion of people in walkway corridors. This infrequent accumulation of people at walkways is preferable to accumulation at station platforms (32). Because accumulation at the platform restricts movement and increases the station stop time. In turn, this increases delays to the vehicles and reduces the line haul capacity.

Platform dimensions are adopted according to the number of passengers for a specified period. If there are more passengers than the train capacity, they must wait beyond the platform area. This is because of economy and reducing delays. Longer and wider platforms cost more and the waiting passengers create congestion on the platform and delays occur to the boarding and alighting passengers. In some cases, multi-stage platforms help accommodate waiting queues. These waiting queues and the concentration of passengers for a specific time can be reduced by more frequent operation. This is possible by the use of shorter trains with shorter headways.

3.3.4 Line Haul Capacity

The final net capacity that is affected by access/egress, stairs, escalators, walking corridors, station platform and vehicle capacity is the line haul capacity. At this stage the LOS criterion is incorporated into the system. Here the minimum headways, the actual maximum passengers and the financial ability of the operator all influence the actual capacity.

Lane/track capacity of a rapid transit system is defined as seats per hour and passengers per hour to be carried in any one direction. The World Bank estimates of rapid transit capacity for various transit systems are reported in Table 3.1. The figures shown are the maximum number of passengers that can be carried on a single lane/track past a point during one hour. These numbers reflect higher utilization, efficient operation and higher patronage (38).

The capacities estimated for Calgary and Ottawa-Carleton are shown in Table 3.2. The Transitway capacity shown in Table 3.2 is based on Standard Bus and 250 buses/hour with off-line stations. The LRT capacity is based on 60 trains/hour with 4 cars/train. The Calgary Transit has also used 30 trains/hour with both 3 and 5 cars/train (13,39). The values shown for Calgary's LRT system are based on 0.17 square metres per standing passenger, which reflects the maximum practical capacity. This is only possible under crush load conditions. The differences among capacities reflect assumptions of vehicle capacity, load factors and comfort criteria.

The estimation of lane/track capacity is governed by the capacity of the vehicle itself, service frequency, length of the train and the station or platform length. These factors are explained in more detail in the following section.

Table 3.1: Urban Transit Capacity

System Character- istics	Buses in Mixed Traffic	Buses Only Lanes	Transitways	LRT Surface Exclusive
Cars/Train	-	-	-	3 to 6
Lane/Track Capacity: Pass/h	10,000- 15,000	15,000- 20,000	30,000	20,000- 36,000
Average Overall Speed, Km/h	10-20	15-18	15-30	15-25

Source: Reference 38

Table 3.2: Transitway and LRT Capacity

City	Transitway		LRT	
	Seats/h	Pass/h	Seats/h	Pass/h
Ottawa- Carleton Studies	12,500	16,000	11,500	19,200
Calgary Transit	-	-	-	14,400- 24,000

Source: Reference 13, 39

3.3.5 Vehicle Capacity

Due to the long operating history of the motor bus, the dimensions of the vehicle, seating configuration and number of seats can be established for given services with much confidence.

The LRV is still in the development stage. Its dimensions vary from one manufacturer to other. This results in a variety of seating configurations. The LRV selection for a specific location is usually based on the geometry of the track and the clearance of the structures.

Seating capacity of vehicles and their space requirements are well-documented in the literature (25,28,33). With urban transit there is always expectancy of standing passengers, therefore, the number of seats provided is influenced by the space available for standees. Giving higher comfort levels will reduce the space for standing passengers, which will in turn reduce system capacity. This is why transit systems cannot compete with private automobiles.

Seating Capacity

In typical urban rail transit, a space of 0.28 to 0.46 square metres per seated passenger is provided. In urban bus transit, 0.28 to 0.37 square metres space is provided per passenger (28). To some extent the rail transit provides more space per seated passenger. This makes rail transit more comfortable for seated passengers than bus transit.

Vehicle capacities for both bus and LRV are shown in Table 3.3. The

Table 3.3: Vehicle Dimensions and Capacities

VEHICLE DIMENSIONS	STANDARD BUS	ARTICULATED BUS	ARTICULATED LRT
Length - m	12	18	24.4
Width - m	2.6	2.5	2.65
PERFORMANCE			
Maximum Speed - km/h	88	88	80
Acceleration - km/h/sec	0.90	0.90	1.00
Deceleration - km/h/sec	1.34	1.34	1.30
CAPACITY			
Available Floor Space for Passenger - sq.m	24.35	38.80	45.30
a) Maximum Seat Capacity	51	68	88
i) Space Occupied by Seats - sq.m	17.85	23.80	30.80
b) Standees			
i) Space for Standees -sq.m	6.5	15	14.50
ii) Comfort Standees	26	60	58
iii) Crush Standees	52	120	116
c) Crush Capacity	103	188	204
d) Design Capacity with Comfort Standees	77	128	146
e) Schedule Capacity with Comfort Standees Load Factor-80%	62	102	117
Station Stop Time-sec	22.2	22.2	15.0
Turnaround Time-sec	120	120	300

Source: Reference 13, 25, 40

numbers shown in Table 3.3 are based on OC Transpo's comfort standards, which reflect the number of seats with free movement between seats and doors (40). On a per seated passenger basis, a 0.35 square metres area is provided.

Standing Capacity

The standing capacity of the vehicle is the remaining space excluding seats and non-usable area. The space criterion for standing passengers in urban transit vehicles is given by numerous studies but a general guideline is shown in Table 3.4. A similar criterion is shown by Pushkarev-Zupan (33) for the evaluation of rail comfort level. The Highway Capacity Manual (28) suggests minimum space per standee at maximum schedule load of 0.22 to 0.26 square metres. DuWang light rail vehicles, which are used by Calgary, Edmonton and many others, commonly provide a space of 0.25 square metres per standee. Ottawa-Carleton Transitway study assumed a space of 0.25 square metres per standing passenger. The values shown in Table 3.3 are based on the same criterion.

Design Capacity

The design capacity of a transit vehicle is the sum of the number of available seats and the number of standees. These standees are comfortable standees (0.25 square metres space per standee) and crush standees (0.17 square metres space per standee). Non-uniformity of passenger demand for various corridors at various locations sometimes causes crush capacity (28). Crush capacity is the maximum practical capacity, based on 0.17 square metres per passenger. In North America,

**Table 3.4: Space Requirements for Standing Passengers in
Public Transit Vehicles**

Passenger Mobility	Area Per Passenger (sq. m.)
Free Circulation	1.03
Minimum Without Physical Contact	0.3 - 0.7
"Crush Condition"	0.2 - 0.3

Source: Reference 25

this situation rarely occurs during the peak period. Based on the author's own experience in Pakistan, during peak period, urban transit often reflect this situation. This results in overcrowding and discomfort to all passengers — including those seated. Since the design capacity (with comfortable standees) can not be maintained throughout the route or operating period, therefore, this should not be used for capacity analysis. The values are shown in Table 3.3.

Schedule Capacity

The transit operator must be able to cope with the variation of passenger load at different locations on the same line, so a reduced capacity (other than the actual design capacity) is used. This is called the Schedule Capacity. The design capacity multiplied by an appropriate load factor gives the schedule capacity. This is also a measure of LOS by the operator. The load factor varies from one area to another and is based on the operator's previous operating experience. In actual practice this capacity is used to determine the fleet size. The values for 80% load factor are shown in Table 3.3.

3.4 Service Frequency

The hourly number of buses or trains is based on specific volumes to be served. Vehicles running close to each other give maximum service frequency. From these considerations, minimum and maximum headways are estimated. The extent of approaching minimum headways depends largely on:

- a) the patronage to be served;

- b) the length of station platform;
- c) the type of station (on-line vs off-line);
- d) station stop time;
- e) the performance characteristics of the vehicle; and
- f) the method of control.

The movement of LRV is controlled with signals. With Transitway, the vehicle is manually controlled by the driver.

The signal system used in rail rapid transit is usually the block signal system. The system may be either the wayside or cab type. A single track is used by trains only in one direction, since trains cannot overtake each other. The main purpose of the signal system therefore, is safety. In other words, the avoidance of rear-end collisions. It also means that the signal system controls the movement of two consecutive trains.

With wayside signal, one block consists of three electrically insulated segments. These signals are installed beside the track. When the train enters each segment, the driver gets information about the next segment and acts accordingly.

In the cab signalling system all the information items are received by the driver inside the cab.

The main difference between the two systems is that in the cab signal system, the driver gets the changing information continuously as the train proceeds. In the case of wayside signal, information displays do not change until the driver is in the same segment of that particular block.

The principle of signals is based on safe stopping distances (32). Safe

stopping distances are also called minimum headways. The minimum headway is based on station stop time, the length of the train, operating speed (over the three segments of the block), driver reaction time and acceleration and deceleration of the vehicle (25,32). These factors and their relationships in formulas for wayside and cab signals are reported in Lang and Soberman, and Soberman and Hazard (25,32).

With rapid transit, 90 seconds headways (40 trains/hour) result from the above formulas. Due to uncertainties of the values of some of the factors, values in actual practice are about 120 to 130 seconds (28 to 30 trains/hour). The results of these formulas are also affected by the operating speed because in actual practice the speed might vary from one block to the other.

Observed frequencies in North America for rail rapid transit fall below 30 trains/hour — with the exception of the New York's two lines where 38 and 32 trains per hour operate respectively (28). Typically headways greater than 4 minutes are experienced when volumes fall below 10,000 persons per direction (33).

The LRT systems operating at present have headways ranging from 5 minutes at Edmonton and Calgary to 30 minutes at San Diego (California). Control technology and a grade separation in CBD area can minimize headways to a certain extent.

Buses on the busway (exclusive ROW) can operate at headways of 15 seconds if an on-line station is used. In the case of off-line stations, 7 seconds headways can be achieved (25). Shorter headways for buses in comparison with LRT system have been reported both for services making stops at every station and non-stop service (28). The minimum theoretical headway for Calgary's LRT system with the existing

control technology will be 150 seconds when 5 cars/train are operated in the future (13).

3.5 Train length

LRT-based systems with the advantage of coupling 6 cars per train, can accommodate 17,000 passenger per hour. To carry these passenger, 276 standard buses or 165 articulated buses are required.

With the LRT system, this advantage is limited by the number of cars available (i.e., at extra costs), passenger volumes, control technology and the length of the station platform.

If the platform length permits, increasing the train length from 3 cars/train to 4 cars/train will results in a 33% gain in passenger capacity for a single track in one direction (assuming 24 trains/hour). Similarly with 20 seconds headway, 60 buses can be operated per berth of a 3 berth station (28). The capacity can be increased by 33% with the increase of one berth. The same volume can be served with 19% less vehicles if articulated buses are used.

In practice, a compromise is made among all the theoretical factors that affect capacity. Train length, headways, actual ridership, level of service and costs are taken into account.

With the rapid transit system, the theoretical capacities are more than those actually anticipated. Design flows of 41,000 hourly passengers for Transitway and 24,300 for LRT system are suggested (25). Realistically these volumes can rarely be anticipated because of limiting factors.

The Ottawa-Carleton Transitway system with CBD surface operation was developed based on a volume of 15,000 passengers per hour. The system is still not completely constructed, but to carry 16,000 passengers per hour (as compared to 41,000 as stated above), the RMOC may build a twin tunnel in the CBD area. The Calgary's LRT system, which is a twin-designed facility for 14,400 passenger hourly capacity, serves only 6,300 passengers per hour.

Building and operating a rapid transit system is not based only on the volume of passengers to be carried but other transit-related impacts as well.

In practice, a compromise among all theoretical factors related to capacity, and other factors such as political issues, transit impacts on other traffic, better uses of the system and the provision of transit services to the majority of the urban area are required.

CHAPTER 4

LEVEL OF SERVICE OF TRANSITWAY AND LRT SYSTEMS

4.1 Overview

Level of service (LOS) for an urban transit system is a more complex subject than highway LOS. The measurement of quality of service must include most service characteristics (5). These characteristics impact on the the users and the operator in a non-uniform manner because they measure LOS in different ways. The user and operator perspectives of LOS are shown in Table 4.1.

Users usually perceive LOS in terms of: overall speed, service frequency, access to the system, number of transfers, ride quality, comfort and convenience (e.g., seat availability, short walk to station, schedule adherence). Public transit is also a public service so users are not willing to pay higher fares.

The operator is interested in the quality of service provided and other factors of LOS including area coverage, increased patronage, short and long range impacts of service, total cost and overall average speed. The operator view is also called service performance. In actual practice each operator works toward offering an efficient and effective service. User needs are used as guidelines to service design.

Users want cheap, convenient and efficient service. In the absence of these key factors even an expensive service becomes unattractive (41). The most successful and attractive service is the one that, in addition to time and cost attributes, runs frequently and provides a one-seat ride.

Table 4.1: Urban Transit Level of Service Characteristics

Level of Measurements	
User's Perspective	Operator's Perspective
Overall Speed	Area Coverage
Service Frequency	Total Costs
Access to System	Quality of Service
One-seat Ride	Patronage
Short Walk to Station	Short & Long Range
Ride-quality	Impacts
Schedule Adherence	
Personal Costs	

4.2 Urban Transit Trip

A typical door-to-door urban trip can be divided into ten parts. Figure 4.1 shows this information in a diagrammatic form.

Start of the trip:

- 1) Walk to feeder bus stop;
- 2) Wait at feeder bus stop;
- 3) Ride on feeder bus;
- 4) Transfer to rapid transit;
- 5) Wait at rapid transit station;
- 6) Ride on rapid transit;
- 7) Transfer to connecting bus;
- 8) Wait for connecting bus;
- 9) Ride on connecting bus; and
- 10) Walk to destination.

End of the trip.

An urban transit trip usually consumes time in two parts. Part of the door-to-door trip time is spent in-vehicle. This is called ride-time. The other part includes waiting, walking and transferring. This second part is called non-ride time.

Only three parts of the trip are allocated to riding. The remaining seven parts include non-ride activities such as walking, transferring and waiting. Direct access to a rapid transit station is an important factor because it reduces the total trip time. For example, if the rapid transit station is within walking distance, then the complete trip consists of only four parts.

Figure 4.1.1 Door-to-Door Urban Transit Trip

The non-ride time is the most severe and disliked part of the trip. One study concluded that ride-time is preferred 2.3 times more than walking, 3 times more than waiting and 5 to 6 times more than transferring (25). Many attitude surveys have reported a preference for elimination of transfers and waiting times (5,25).

Access to an urban transit station is by walk, park-and-ride, kiss-and-ride and feeder buses (see Figure 3.1 in Chapter 3). Those who walk and feeder bus users may be "captive" users; on the other hand, the park-and-ride and kiss-and-ride users are generally "choice" users.

4.2.1 Walk

Walking distance and the behaviour of the transit users have been studied extensively by other researchers (37,42,43,44). There is a variation in reported distances due to conditions at specific locations and assumptions related to surveys carried out. The relationship between walk and distance in several countries is shown in Figure 4.2. The least walking distance was found in the U.S. Canadians were found to walk a little further and Europeans were found to walk longer than the North American. This may be related to weather conditions, socio-economic status and the availability of private automobiles.

A study carried out in Washington, D.C. concluded that transit users with low socio-economic status walk longer distances than those with higher socio-economic status. The survey did not take sex into account and only commuters without automobiles were considered (42).

The effect of walking distance on ridership has been assessed in different

Figure 4 2. Walking Distance and its Impacts on Urban Transit Ridership

Source Reference 25

surveys (43). One survey found that 50% of all transit users walk less than 150m and very few walk more than 600m (25). Another survey in a low density area showed that at 200m, the ridership is 3 times higher than that at 400m (43). A detailed study of the transit users' walking behaviour was done in Vancouver (44). The study included zone of influence for station assessments. The results of this study were compared with those of European studies. A range of walking distances (from 214m to 350m) was determined for North American conditions. The walking behaviour of North Americans and Europeans was found to be similar as shown in Figure 4.2. The corresponding values for Europe are 275m to 396m. Various transit operators still use 400m an acceptable walking distance as a rule of thumb (5).

Walking distance can be minimized by spacing stations closer together — but at the expense of increased capital costs and reduced average overall speed. To optimize station spacings, therefore, both the operator costs and the user access costs must be taken into account.

4.2.2. Park-and-Ride

Two types of commuters are included in park-and-ride. Those who live in suburban communities and work in downtown and those who live downtown and work in the suburbs. They cannot take the automobile to work with them because of either a lack of parking within walking distance or the high cost of parking in general. This means that individual car owners use their own decision-making criteria (i.e., cost-benefit criteria) in deciding whether to take their automobile to work or not. The availability of parking at CBD terminals and outlying stations is

an incentive to park the automobile at these locations and use transit.

4.2.3. Kiss-and-Ride

These are users who share the automobile with other members of the family. The possibility of no feeder service at their doorstep or inconvenient feeder service plays an important role in deciding to use the kiss-and-ride service.

4.2.4 Feeder Bus

The users of the feeder bus are those who work at the rapid transit station or in its surrounding land uses or want to transfer to rapid transit. Other users who could also be included have a longer ride mainly on line haul facility.

All means to reach a rapid transit station (except walking) consume money and time both. With kiss-and-ride type of mode, the time consumption is more due to the involvement of two persons. Park-and-ride is more expensive than kiss-and-ride and feeder buses (6). The major group (i.e., captive users) of the rapid transit rely on feeder buses. The Transitway can serve these riders better than rail transit by providing a one-seat ride that eliminates transfers and waits at the rapid transit station.

The factors that influence non-captive users and provide a high LOS to the captive users include average overall speed, number of transfers and service quality. Each of these factors is explained in the following sections.

4.3 Average Overall Speed

Average overall speed of a rapid transit system is derived from the acceleration, deceleration and maximum speed of the vehicle. Analytical procedures for the calculation of average overall speed between stations or for the entire route have been explained in detail in the literature (25,32,45,46). This computed average overall speed reflects the performance characteristics of the technology used and not the views of the users. The performance characteristics for vehicles used in the calculation of average overall speed are given in Chapter 3 (Table 3.3).

Speed can be increased by either eliminating stations (station stops) or spacing them further apart. The effects of station stop time and spacing for a 6 km route serving 4,000 passengers in a peak hour for an articulated bus are shown in Table 4.2. It is to be noted that turnaround time at the end of the route is included in the computations.

It is clear from Table 4.2, that the further the stations, the higher average overall speed. An increase in station stop time also results in reduced average overall speed. But as station spacing increases, the effect of station stop time decreases.

4.4 Number of Transfers

For an origin-destination trip of an urban transit, the majority of riders experience a minimum of one transfer. Transferring is the most disliked part of an urban transit trip and becomes much worse when the rapid transit is not able to meet its schedule. Frustration increases when the transfer is made from a frequent service to an infrequent service (e.g., from a rapid transit to a connecting bus operating on

Table 4.2: Effects of Station Spacing and Stop Time on Overall Speed and Fleet Size

Station Spacing (km)	Station Stop Time (sec)	Overall Speed (km/h)	Variation in Fleet Size
1	22.2	34.02	14
1	44.4	28.12	17
2	22.2	43.19	11
2	44.4	38.11	13
3	22.2	47.45	10
3	44.4	43.23	11

city streets).

A recent survey by New York and New Jersey (U.S.A.) transit authorities concluded that the users dislike the trip in pieces. This is one of the main reasons for the decline of the use of urban transit (47). Transit authorities have been trying to give transferring a purpose to relieve the tension of the waiting passengers. The search resulted in huge timed-transfer focal point stations.

Timed transfer has been in use in Europe for a long time. Edmonton was the first city in North America to adopt this system in 1972 (48). It was later followed by Toronto, Ottawa, New York, Calgary and others. An actual true timed-transfer and integrated system does not yet exist but a few successful timed-transfer and integrated systems are operating in Europe and in Toronto (49).

The practical integration of service on an area-wide basis is a difficult task. Surveys show that in Toronto, during the afternoon peakhour, passengers have to wait for 3 to 6 trains until they board one, regardless of the train length (50).

The main advantage of the Transitway over rail system is that it keeps the transfer time to a minimum because of frequent service. It also provides a one-seat ride from door-to-door for most riders.

4.5 Service Quality

Service quality of an urban transit system is defined by ride quality, safety, seat availability, cleanliness and possibly aesthetics. The most important factors from the user point of view are, however, ride quality, safety and seat availability. The LOS factors discussed earlier in some literature sources are also included in the

broad definition of service quality.

The LRT system provides a good quality ride between stations because of its technological characteristics. The Transitway, using buses on exclusive ROW with higher speeds, also provides a good quality ride. The modest riding experience of buses (especially articulated buses) on exclusive ROW in urban environment, means that a full response about ride quality is not yet complete.

Seat availability depends on the frequency of service. The more frequent the service, the fewer number of passengers loaded at each stop and the greater chance of seat availability. Transitways dominate rail transit in this respect because of single unit vehicle operation.

4.6 Travel Time for An Origin-Destination Trip

A number of studies have shown the effect of route length for feeder and connecting services on the total origin-destination trip time for a specific urban transit service (10,12). Analyses were considered for various route lengths and numerous operating assumptions.

An attempt is made here to find the ride and non-ride times for Transitway and LRT systems. A case study is developed. A rapid transit route length is connected with feeder service at one end and with a connecting service (distribution service) at the other end. For a number of scenarios the quantitative results are shown in Table 4.3. Figure 4.3 shows the simulation method used to arrive at the various time components. Related computations are explained below.

Table 4.3: An Origin-Destination Trip Time

Trip Portion	Distance Portion	Travel Time (min) Transitway	LRT
FEEDER SERVICE			
Walk to feeder bus stop	400	5	5
Wait at bus stop	-	0.73	2.5
Feeder bus ride	4000	12.66	12.66
Transfer to rapid transit	-	1	1
RAPID TRANSIT SERVICE			
Wait at rapid transit station	-	0.37	1.25
Rapid transit ride	10000	14.30	13.28
Transfer to connecting bus	-	1	1
CONNECTING SERVICE			
Wait for connecting service	-	0.73	2.5
Connecting bus ride	4000	12.66	12.66
Walk to destination	400	5	5
Schedule delay	-	<u>0.56</u>	<u>1.05</u>
Total time	-	54.01	57.90
Ride time	-	73.36%	66.67%
Non-ride time	-	26.64%	33.33%

Figure 4.3: Simulation of Origin-Destination Travel Time by Transitway and LRT

ASSUMPTIONS

WD = 400 meters

WV = 80 meters per minutes

FRL = CRL = 4000 meters

RRL = 10000 meters

SS = 1000 meters

VF = VC = 316 meters per minute

WT = $1/2 \times$ headway

TT = 1 minute

SD = 15% $\times$ (WT+TT)

Bus type = Articulated

Where:

WD = Walking distance to station

WV = Walking speed

FRL = Feeder bus route length

CRL = CBD area route length

RRL = Rapid transit route length

SS = Station spacing

VF = VC = Average overall speed of feeder & connecting mode

WT = Waiting time (at a bus stop or rapid transit station)

TT = Transfer time (to rapid transit or connecting service).

SD = Schedule delay

CALCULATIONS

Frequency and Headways:

Frequency of 24 trains/hour and a train length of 3 cars is assumed for the LRT system. This is a practical frequency in North America with a headway of 2.5 minutes (25). Train length can be increased to 5 cars/train but this would reduce the frequency of the LRT system and give more time advantage to Transitway service.

1. Capacity

Capacity is calculated as follows;

$$\begin{aligned}\text{Capacity} &= \text{Train length (cars)} \times \text{frequency} \times \text{capacity per car} \\ &= 3 \times 24 \times 117 = 8400 \text{ passengers/hour}\end{aligned}$$

To serve that volume by Transitway, we would need 83 articulated buses with a headway of 0.73 minutes. The headway is calculated by the equation given by Reference (46) and is shown in sub section 4.7.2. The vehicle's capacity and other related values (for bus & LRT) are taken from Table 3.3 of Chapter 3.

2. Travel Time

The basic formula for the calculation of travel time used is:

$$T = D/V$$

Where

T = Travel time in minutes

D = Distance travelled in meters

V = Speed in meters per minute

From this formula the corresponding travel times for walk, feeder route, rapid transit route and connecting mode routes are calculated. Calculations are based on data given above.

3. Speed for Rapid Transit Route

The basic formula for average overall speed calculation is used here (25).

$$AV = (RRL / M) \times 60$$

Where

AV = Average overall speed (m/min)

M = ((NS x (T + V/2a + V/2d) + RRL/V), and

NS = (RRL / SS)

RRL = Rapid transit route length (m)

NS + 1 = Total number of stations (number)

SS = Station spacing (m)

T = Station stop time (sec.)

V = Maximum Speed for bus and LRV (m/sec.)

a = Acceleration (m/sec./sec.)

d = Deceleration (m/sec./sec.)

The values for T, V, a, and d are taken from Table 3.3 of Chapter 3

and total travel time is divided into the following parts:

$$\text{Percent Ride Time} = \frac{(\text{Feeder ride time} + \text{rapid transit ride time} + \text{connecting service ride time})}{\text{Total travel time.}}$$

$$\text{Percent Non-Ride Time} = 100 - \text{Percent ride time}$$

where

$$100 = \text{percent ride time} + \text{percent non ride time.}$$

4.6.1 Interpretations of the Results

As is clear from Table 4.3, due to more frequent service, the non-ride time for Transitway is 20% less than that for the LRT system. Also the total time for Transitway is 7% less than the time taken by the LRT system. Results of another simulation study are shown in Figure 4.4. This study assumes an increase in feeder and connecting route lengths from 4 km to 6 km for the Transitway case only. By increasing feeder and connecting route lengths, the total door-to-door time for the LRT system is reduced by 13% compared to the Transitway service. But the ride-time of Transitway is still 18% more than that of the LRT system. The feeder and connecting route lengths for the LRT system are increased from 4 km to 6 km in another case. The results are shown in Figure 4.5. The total time for a complete trip of the Transitway takes 31% less time than that of the LRT system.

From the results of Figures 4.4 and 4.5 it is concluded that for an origin-destination trip, the total time taken by the LRT system increased more than that for the Transitway case with similar increase in feeder and connecting route lengths. To equate the trip time the LRT rapid transit route length has to be extended.

When the same bus is operated from door to door and uses the Transitway as a part of total trip length, the Transitway service is superior (see Figure 4.6). The case in Figure 4.6 shows the total time for a complete trip for the LRT system is 15% more than the Transitway.

These results show that with the Transitway operation, longer feeders and connecting services can be operated compared to LRT system. Transfer and waiting

Figure 4.4: Origin-Destination Trip Time When Transitway Feeder Length is Increased at Both Ends

Figure 4.5: Origin-Destination Trip Time When LRT Feeder Length is Increased at Both Ends

Figure 4.6: Origin-Destination Trip Time for Transitway Integrated Service versus LRT

times are also much less than the LRT system. Total ride time is higher than non-ride time for the Transitway case.

All time components shown in the tables and figures are actual clock times. If psychological weights are assigned to transferring, waiting and walking activities, the results would be more favourable to the Transitway system.

4.7 Level of Service Simulation

4.7.1 Overview

The rapid transit appraisal study conducted for Ottawa-Carleton resulted in three options for further detailed considerations (39). These are:

- 1) Construction of 40 kms (25 miles) of Transitway, or
- 2) 40 kms (25 miles) of Tramway, or
- 3) 11 kms (7 miles) of LRT with the use of a tunnel in the CBD.

Besides the cost and staging flexibility, one of the reasons for favouring the Transitway option was the provision of higher LOS to the entire urban and suburban areas.

The highly populated suburban communities, namely Kanata, Barrhaven and Orleans are about 20, 24 and 17 kms away from the CBD of Ottawa respectively. In providing a direct service (i.e., one-seat drive) from the urban communities, the Transitway option was found to be the most compatible with the future land use projections for the RMOC.

4.7.2 Simulation Model

In order to compare LOS of Transitway and the LRT system, a simulation model (shown in Figure 4.7) was developed. This simulation model is based on the entire region of Ottawa-Carleton (see Figure 4.8.). This figure shows the various urban communities, the Transitway, future extensions, employment centers in the area, and the areas where express service has already been provided by OC Transpo.

1. Transitway Case

Transitway services that are bound for CBD are of two types:

- 1) express service; and
- 2) non-express service.

The two services differ in terms of travel time. The minimum time advantage of express service over the non-express service should be 5 minutes (12). To make the express service more attractive to the users, a 10 minute advantage over the non-express service is preferred. At this point the bus service will have an advantage over automobile for door-to-door trips in terms of travel time (12). The Ottawa-Carleton Transit Commission also defines the express service in a similar way (53).

In this simulation model, the total route length considered consists of three portions:

- 1) the feeder route length;
- 2) the Transitway route length (exclusive facility); and

(a) Transitway Case

(b) LRT Case

Figure 4.7: Level of Service Simulation

Figure 4.8: The Ottawa-Carleton Region and Transitway

Source: References 51, 52

3) the CBD area route length.

Since the station spacings vary from one portion to the other, the travel time for the non-express service is calculated for the entire route. The travel time for express service is assumed to be 10 minutes less than that of non-express service time.

Normally an urban area of 25,000 to 50,000 population can successfully carry its transit operations with only non-express service. When the population exceeds 250,000, the non-express service needs to be supported with express service. With these two services the urban area is better served than if non-express service is operated (12). About 25 to 30 percent of services should be allocated to the express category for a population of about 1 million without rapid transit as a suggested guideline (12).

The operation of many services on public roads and streets creates discomfort for other users due to increased number of transit vehicles that create congestion. The percentage of express service can increase (if required) somewhat, provided that exclusive ROW is available. In the Ottawa-Carleton case, the Transitway is used as a part of the overall route and provides 40% express services (30). This percentage can be increased if necessary.

In Ottawa-Carleton all the express services are one-way only. Following the completion of an assignment, an express bus never returns to the same route for a second trip. The bus deadheads instead to the nearest bus stop and starts a new service. This way, in a particular period, one bus is used for a variety of services and many routes. This type of scheduling is based on a computerized programme. According to OC Transpo, by using this method, they reduced their fleet size by 10%

to 12% (30).

The literature suggests that buses operating on local streets attain an average overall speed of about 10 mph (16 km/h) to 12 mph (19 km/h). But express buses or those that use the freeway lanes can reach up to 40 mph (64 km/h). An intensive study by Levinson (54) categorized the average speed of buses in three different types. The study was based on a wide cross-section of U.S cities. The values given for the speed in CBD area, central city area and in the suburb were 8.5 km/h, 16 km/h and 23 km/h respectively. The values were also compared with automobiles.

In practice there is a wide variation in the number of transit passengers bound for the CBD in different cities. For example, in Kitchener-Waterloo (1976), 65% of the daily passenger trips either originate or terminate in the CBD. This percentage is 72% for Windsor and 60% for Toronto (25). In 11 cities in the U.S, the CBD trips made by transit ranged from 31% to 78% of total trips (32). As the city size decreases, the percentage increases. The reason may be the concentration of employment and all other activities in CBD as well as the urban form. The percentage is also high for older cities with wider and dense CBD areas. This percentage may vary widely for today's cities where the population and activities are scattered throughout the urban area.

The patronage statistics for Ottawa-Carleton Transitway are shown in Reference (39). These figures show the peak hour passenger volumes generated by each area. In this LOS simulation, 60% of the peak hour volume is assumed destined for the CBD. As shown in Figure 4.8, there is no express service inside the greenbelt area. The reason is that all the services within 15 minutes to the

Transitway stations are direct feeders and they can carry the passengers to all important activity centres of the urban area within a 34 minute journey (30,51). The peak hour passengers destined for the CBD for each urban community are shown in Tables 4.4 & 4.5. The number of passengers for Kanata, Barrhaven and Orleans are the actual figures given in Reference (39). The numbers for Nepean Centre and Shopper City area are calculated from the screen line values and are an approximation only. Because of the high number of people in the greenbelt and the inadequate information about how many of them are going to CBD via Transitway, a total of 15,000 passengers were estimated to be bound for CBD in a peak hour.

The layout of the Transitway (see Figure 4.8), is supposed to serve 15,000 peak hour passengers (30,39). The various urban communities, passenger volumes (the sum of the volumes is 15,000 passengers per peak hour) and the corresponding distances to the final destination are shown in Tables 4.4 and 4.5.

The feeder route lengths were scaled from OC Transpo's system map (52). The Transitway and CBD area route lengths are the actual ones as used. Two routes of express service, which are very long and serve only a small volume of passengers, are ignored. Also the assumption of a 10 minutes time advantage of express service does not seem realistic here because of very long route lengths. One of these routes serves the Richmond/Munster area in the west suburb and the other the Manotick/Kars area in the southwest suburb. Such routes would be never used as a feeder service to the LRT system. Instead they would probably be direct express or non-express services to the CBD.

The peak hour volume for an individual area is divided into the ratio of

Table 4.4: Transitway Overall Speed for Various Urban communities
(Includes Walking Time)

Articulated Bus								
Variables		Travel Time (minutes)						
Urban Community	FRL (km)	RRL (km)	CRL (km)	Pk.Pass /hr/dir.	Express Service	Non-Express Service	Weighted Time (hour)	Weighted Speed (km/h)
Kanata- CBD Ottawa	9	11	3	3300	53.40	62.51	+ 0.98	# 24.29
Nepean Centre- CBD Ottawa	7	13	3	900	58.11	64.85	1.04	22.88
Barrhaven- CBD Ottawa	9	13	3	2400	57.26	66.04	1.04	24.81
Orlean- CBD Ottawa	11	6	-	3000	40.46	49.48	0.76	23.42
Shopper City Area- CBD Ottawa	4	6	-	1650	24.73	32.66	0.49	22.04
Central City- CBD Ottawa	5	5	-	3750	-	42.60	0.71	15.21

Note:

+ = [(53.40/60 x 40%) + (62.51/60 x 60%)]

= (9+11+3+.8)/.98

0.80 = Walking Distance of 400m each at both ends of the trip.

FRL = feeder route length

RRL = rapid transit route length

CRL = CBD area route length

2

NEC

Table 4.5: Transitway Overall Speed for Various Urban communities
(Excludes Walking Time)

Variables	Articulated Bus					
	Travel Time (minutes)			Weighted Time (hour)		Weighted Speed (km/h)
Urban Community	FRL (km)	RRL (km)	CRL (km)	Pk.Pass /hr/dir.	Express Service	Non express Service
Kanata-						
CBD Ottawa	9	11	3	3300	43.40	52.51
					+	0.81
						28.39
Nepean Centre-						
CBD Ottawa	7	13	3	900	48.11	54.84
						0.87
						26.44
Barrhaven-						
CBD Ottawa	9	13	3	2400	47.26	56.04
						0.87
						28.74
Orlean-						
CBD Ottawa	11	6	-	3000	30.46	39.48
						0.60
						28.33
Shopper City						
Area-						
CBD Ottawa	4	6	-	1650	14.73	22.66
						0.32
						31.25
Central City-						
CBD Ottawa	5	5	-	3750	-	32.15
						0.54
						18.52

Note:

+ = [(43.40/60 x 40%) + (52.51/60 x 60%)]

= (9+11+3)/0.81

FRL = feeder route length

RRL = rapid transit route length

CRL = CBD area route length

express and non-express service. Then the headways for express and non-express services are calculated.

Travel time components

The basic formula for the calculation of travel time and the assumed walking distance and walking speed are the same as used in section 4.6. Since all the express service areas are beyond the limits of the central city, 23 km/h (380 m/min) average speed on the feeder route length is assumed. In one case only, a speed of 12 km/h (200 m/min) is assumed for central city feeder route length. These assumptions for speed values are based on the above explanation. Average overall bus speed while running on Transitway's (exclusive) route length is determined by the same formula as shown in section 4.6 and is converted to km/h. The length of the CBD portion in Ottawa-Carleton is 3 km. Due to closer station spacing the average speed in this area reaches 16 km/h (265 m/min.) only.

Now that all the distances and the corresponding speeds are known from origin to destination, with the above formula, the travel time for each segment can be calculated. Waiting time is taken as half of the corresponding headways waited for.

Headways for the Transitway case as well as for the LRT system are found by the equation given by Morlok (46):

$$\text{Headway (minutes)} = (N \times Q)/q \times 60$$

Where,

N = Number of cars per train

N is one in the case of bus and more than one for LRT

Q = Capacity of a car or bus

q = Total number of passenger per hour

Schedule delay is added as 15% of the waiting and transfer time. In the Transitway case there is no transfer time. The summation of all the time components gives total time for an origin-destination trip.

Weighted time

$$\begin{aligned} \text{Weighted time} = & ((\text{Total time taken by express service}) \times 40\% \\ & + (\text{Total time taken by non-express service}) \times 60\%) \end{aligned}$$

Where 40 and 60 are the percentages for express and non-express service respectively.

Weighted Speed

The distance travelled from origin to destination divided by the weighted time results in weighted speed. Therefore:

$$\text{Weighted speed} = \text{Total route length} / \text{weighted time.}$$

This weighted speed includes walking time. The results are shown in Table 4.4.

Another simulation is run with similar data and assumptions but excluding the time spent walking to the station. Table 4.5 shows the corresponding results.

2. LRT Case

Since LRVs cannot operate off the track, the passengers must reach the station by other ways.

As stated earlier, in the U.S, more than 90% of the passengers reach the station by feeder buses or private automobiles. In Edmonton, 90% of the passengers

reach the LRT station by feeder buses also (see Chapter 3).

In this LOS simulation, 90% of each urban community's passengers are allocated to feeder buses and 10% are assumed to reach the station by other means. The remaining data and assumptions are the same as used in Transitway case.

Headways for feeder buses and LRT system are calculated by using the above equation. Headways are based on the number of peak hour passengers for the corresponding areas. In this simulation model, the train length has been also taken into consideration. A length of 6 cars/train and 3 cars/train is used.

The total origin-destination time and average overall speed for feeder services and LRT are shown in Table 4.6. The train length used is 6 cars/train. The results also include walking distances. In another simulation the same items are calculated — excluding walking distances. The results are shown in Table 4.7.

From the tables it is clear that the Transitway is superior to the LRT system in terms of door-to-door speed — even if there is no express service (see a central city area where no express service exists). The average overall speeds shown in these tables for Transitway and LRT system do not include turnaround time. The turnaround time if included, will further reduce the speed for LRT system because the turnaround time for LRT system is longer than of the Transitway.

The speed for LRT system can be increased to some extent if shorter trains are operated. A simulation based on the above data has been run for the train length of 3 cars/train. The results in Table 4.8 are for this service. The average speed includes the walking distances. Table 4.9 shows the average speed based on the same data but excludes walking distances.

Table 4.6: LRT System Average Overall Speed for Various Urban Communities
(Includes Walking Time)

<u>LRT/Articulated Bus</u>							
<u>Variables</u>	<u>Travel Time (hour)</u>						
	Urban Community	FRL (km)	RRL (km)	CRL (km)	Pk.Pass. /hr/dir.	Bus LRT	Average Speed (km/h)
Kanata-							
CBD Ottawa	9	11	3	3300	0.498	0.657	20.61 ⁺
Nepean Centre-							
CBD Ottawa	7	13	3	900	0.463	1.03	15.94
Barrhaven-							
CBD Ottawa	9	13	3	2400	0.505	0.75	20.56
Orleans-							
CBD Ottawa	11	6	-	3000	0.587	0.370	18.60
Shopper City Area-							
CBD Ottawa	4	6	-	1650	0.298	0.480	13.88
Central City-							
CBD Ottawa	5	5	-	3750	0.517	0.317	12.95

Note:

⁺ = $(9+11+3+.8)/(.498+.657)$

0.80 = Walking distance of 400m each at both ends of the trip.

Train length = 6 cars/train

FRL = feeder route length

RRL = rapid transit route length

CRL = CBD area route length

Table 4.7: LRT System Average Overall Speed for Various Urban Communities
(Excludes Walking Time)

Variables	LRT/Articulated Bus					
	FRL (km)	RRL (km)	CRL (km)	Pk.Pass /hr/dir.	Bus	LRT
Urban Community						Average Speed (km/h)
Kanata-						
CBD Ottawa	9	11	3	3300	0.414	0.574
Nepean Centre-						23.28
CBD Ottawa	7	13	3	900	0.380	0.94
Barrhaven-						17.42
CBD Ottawa	9	13	3	2400	0.422	0.664
Orleans-						23.02
CBD Ottawa	11	6	-	3000	0.504	0.286
Shopper City Area-						21.52
CBD Ottawa	4	6	-	1650	0.215	0.397
Central City-						16.34
CBD Ottawa	5	5	-	3750	0.434	0.234
						14.97

Note:

+ = $(9+11+3)/(.414+.574)$

Train length = 6 cars/train

FRL = feeder route length

RRL = rapid transit route length

CRL = CBD area route length

Table 4.8: LRT System Average Overall Speed for Various Urban Communities
(Includes Walking Time)

<u>Variables</u>	<u>LRT/Articulated Bus</u>					
				<u>Travel Time (hour)</u>		
Urban Community	FRL (km)	RRL (km)	CRL (km)	Pk.Pass /hr./dir.	Bus	LRT
Kanata-						
CBD Ottawa	9	11	3	3300	0.498	0.596
Nepean City-						+
CBD Ottawa	7	13	3	900	0.463	0.803
Barrhaven-						18.80
CBD Ottawa	9	13	3	2400	0.505	0.663
Orleans-						22.09
CBD Ottawa	11	6	-	3000	0.588	0.302
Shopper City Area-						20.00
CBD Ottawa	4	6	-	1650	0.298	0.358
Central City-						16.46
CBD Ottawa	5	5	-	3750	0.517	0.267
						13.78

Note:

+ = $(9+11+3+.8)/(.498+.596)$

0.80 = Walking distance of 400m each at both ends of the trip.

Train length = 3 cars/train

FRL = feeder route length

RRL = rapid transit route length

CRL = CBD area route length

Table 4.9: LRT System Average Overall Speed for Various Urban Communities
(Excludes Walking Time)

Variables	LRT/Articulated Bus					
	FRL (km)	RRL (km)	CRL (km)	Pk.Pass /hr./dir.	Bus	LRT
Urban Community						Average Speed (km/h)
Kanata-						
CBD Ottawa	9	11	3	3300	0.414	0.512 ⁺
Nepean Centre-						
CBD Ottawa	7	13	3	900	0.379	0.720
Barrhaven-						
CBD Ottawa	9	13	3	2400	0.422	0.580
Orleans-						
CBD Ottawa	11	6	-	3000	0.504	0.219
Shopper City Area-						
CBD Ottawa	4	6	-	1650	0.215	0.274
Central City-						
CBD Ottawa	5	5	-	3750	0.434	0.184

Note:

+ = $(9+11+3)/(.414+.512)$

Train length = 3 cars/train

FRL = feeder route length

RRL = rapid transit route length

CRL = CBD area route length

As longer trains are operationally economical, so operating shorter trains will increase the operating costs. This implies that the provision of frequent services to an urban area necessitates minimised headways with less economical shorter trains. The result would be increased costs.

In actual practice, the Ottawa-Carleton Transitway provides a higher average overall speed than that shown in the reference tables. On the West Transitway, a freeway lane of 9 km length is used and about 3 km of non-stop service (Ottawa River Parkway) is also used for Transitway operations. The speed should, therefore, be more than 23 km/h. Similarly for the East Transitway, a considerable portion of the feeder route length is a freeway lane where much higher speed than that assumed in this simulation could be reached.

In the event that such opportunities exist in an urban area that can increase the speed of feeder buses, there is an incentive to operate direct and express services to the CBD. These services provide access to the CBD that avoids transferring and waiting times at the LRT station. This reduces the total travel time for commuters. Similar routes have been in use in Edmonton (see Figure 2.4, Chapter 2).

It is concluded that the Transitway provides a superior LOS to the catchment urban area in terms of door-to-door travel time, elimination of waiting and transferring, frequent service and availability of seat.

CHAPTER 5

TRANSITWAY AND LRT COST MODELS

5.1 Overview

Cost is a major consideration in decision-making about rapid transit technology and systems. This chapter is devoted to the study of cost of Transitway and LRT systems.

The total cost of an urban transit system consists of two parts: capital costs and operating costs which include maintenance costs. The capital costs increase with the provision of exclusive ROW and is even greater if the facility is constructed above or below ground.

The exclusive facility provides the opportunity to increase ridership and provides rapid mobility due to increased speed. The higher speed in turn decreases operating costs. The operating costs can be further reduced by using longer trains or articulated buses instead of standard buses. There are also numerous methods of operation and various automation means through which operating costs can be reduced.

5.1.1 Theoretical Consideration

Conceptually, urban transit systems can be characterized by a range of volumes (19). This is shown in Figure 5.1. The two extreme cases will be discussed first. On the one hand, the bus operating on city streets in mixed traffic is used for very low volumes (i.e., low population densities). On the other hand, rail rapid transit is the cheapest system for very high volumes (i.e., highly populated cities).

Figure 5.1. Conceptual Representation of Public Transit Cost-Efficiency

Source Reference 19

For medium-size cities, Transitway, the LRT, and ALRT can be used.

It is of interest here to study whether for volumes generated in low to medium density corridors the Transitway option is the cheapest. The ALRT, which is fully automated (i.e., driverless), is preferred to Transitways in areas with higher volumes. The LRT and Transitway are competitors for each other, however for shorter and densely populated corridors LRT is preferred assuming lower operating costs than the bus rapid transit system.

Based on theoretical considerations (i.e., suggested design volumes), an attempt will be made to discover the break-even point for cost in order to study the advantage of one system over the other (see section 5.11).

5.2 Cost Comparison

5.2.1 Previous Analysis

A number of studies in the period of 1965 and 1975 have shown the cost efficiency of the bus rapid transit system compared to the rail rapid transit system. LRT is a relatively new option and was not included in the research. Actual operating advantages of articulated buses, especially on exclusive ROW were also not available during that period. All these studies compared rail rapid transit with standard bus transit. A few studies did, however, include the articulated bus in the analysis based on hypothetical assumptions. Additionally, the capital cost for the exclusive facility was extracted from highways or freeway-based cost statistics. Hypothetical operational methods, longer trains (up to 10 cars/train) and a wide range of theoretical assumptions were the basis for comparison. The findings of a

number of these studies are shown in Table 5.1. This table shows the different peak hour passengers volumes and the corresponding percentages for which the rail rapid transit system is more expensive than the bus rapid transit system. The wide range of peak hour passenger volumes indicates that the results of studies vary according to situational circumstances and other assumptions.

In spite of these intensive studies and the cost-effectiveness of buses, rail was subsidized by the respective governments. Investments were made on the assumption that it plays an important role in land development (22). One LRT proponent recently stated that unfortunately the motor bus was given no opportunity of exclusive ROW in its long operating life (56).

5.2.2 Current Practices

The transit requirements of the area and the fiscal potential of the operator are the basic guidelines for the evaluation of alternatives. The selection of alternatives and the choice among them are usually based on compatibility with the fiscal and operational environment of the area.

Recently, a number of medium-sized cities have upgraded or have been upgrading their transit systems. A majority of these are providing exclusive ROW to make their systems more efficient and cost-effective.

Many cities where the transit system was based on street cars have opted for LRT systems. Very few have built Transitways. These systems (LRT and Transitways) serve as a transition from a small transit system to a large transit system.

Currently there are few Transitways and numerous LRT-based systems

**TABLE 5.1: Results of Previous Comparative Studies for
Rapid Transit Systems**

Study By	Rail Transit is More Expensive than Bus Rapid Transit By	At Peak Hour Volume
Boyd et al.	113%	18,000
Keeler et al.	82%	N.A.
Meyer et al.	25%	5,000 - 50,000
Deen & James	15%-20%	4,000 - 12,000
Hammer, A.M.	0%	20,000

Source: References 7,22,55

operating in North America. For example, in Calgary the busway option was slightly cheaper than the LRT system but was rejected on assumptions regarding the projected future higher passengers volumes. Articulated buses were not, however, included in the analysis. In the case of Ottawa-Carleton, the Transitway was the favoured option. The capital costs of the recommended options for Ottawa-Carleton and Calgary are shown in Figures 5.2, 5.3 and 5.4.

By comparing these figures, it is shown that guideway construction and related property are more expensive for Calgary's LRT system than Ottawa-Carleton's Transitway. The cost figures for Ottawa-Carleton show that the cost for property is much less than Calgary's LRT system. Vehicle cost is higher for Ottawa-Carleton but includes the total number of vehicles needed for the whole urban transit. For Calgary, vehicle costs do not include feeder buses.

The capital and operating costs of various North American transit systems are shown in Tables 5.2 and 5.3. Table 5.2 shows the cost/km for Canadian Transitway and LRT systems. The cost figures indicate that the LRT systems are over two times more expensive than the Transitway system. The Ottawa-Carleton Transitway is only partially in operation and the operating costs for the Scarborough LRT system are not available, so these systems can not be compared on operating costs basis.

The U.S. systems are comparable in terms of capital costs and operating costs. The cost figures show that on the average, LRT systems are over two times more expensive than busway systems. Partially underground LRT systems (Buffalo and Pittsburgh) are more expensive both in terms of capital and operating costs.

Cheap ROW is not the only factor that contributes to the higher cost of LRT

Figure 5.2: Capital Cost of Ottawa-Carleton Transitway
(Standard Bus)

Source: References 36,64

Figure 5.3: Capital Cost of Ottawa-Carleton Transitway
(Articulated Bus)

Source: References 36-64

Figure 5.4: Capital Cost of Calgary's LRT System

Source: References 13,25

TABLE 5.2: Capital Cost for Canadian Rapid Transit Systems

City	System	Length (km)	Capital Cost/km (1987\$)
Calgary	LRT	28.6	24.42
Edmonton	LRT	10.5	28.34
Scarborough	LRT	07.00	30.52
Average	-	-	27.83
Ottawa-Carleton	Transitway	08.40	12.00

Source: References 13,51

Note: i) Costs include vehicles also

ii) Conversion to 1987\$ is made with Reference 57

Table 5.3: Costs for U.S. Rapid Transit Systems

City	System	Length	Capital Cost/km (1987\$ million)	Operating Cost/year
Buffalo	LRT	10.30	111.72	13.97
Pittsburgh	LRT	16.90	63.84	10.77
Portland	LRT	24.30	19.95	07.18
Sacramento	LRT	29.13	13.30	08.65
San Diego	LRT	32.83	11.97	09.58
Average	-	-	44.16	10.03
Pittsburgh	East Busway	10.94	25.27	04.92
	South Busway	06.44	11.97	03.99
Average	-	-	19.00	04.46

Source: Reference 35

Note:

1. Capital Costs do not include Vehicles
2. Annual Operating Costs are for Calendar year or fiscal year 1988. The conversion is made for 1987\$ (References 57,58).

systems. Other factors such as infrastructure and vehicle costs are also considerably higher in the case of LRT systems. These cost figures shown for LRT systems will be much more if the costs for feeder buses are included. The capital costs for any rapid transit system can be reduced to some extent if guideway can be constructed on the surface instead of under or above ground. Also if available free or cheap ROW exists. The operating cost can be reduced only if appropriate ridership potential exists. Longer trains and articulated buses will reduce operating costs.

Modern LRT systems, which operationally are not capable of competing with RRT and ALRT, are the subject of controversial discussions among planners. This is due to higher capital costs and greater operational inflexibility compared to the bus rapid transit system. The recent actual costing and operating experience with Transitways and LRT-based systems fairly compares the two systems.

5.3 Methodological Framework for Cost Estimation

5.3.1 Approach

Two most common approaches to cost estimation are used for evaluating urban transit alternatives or other engineering related studies. One is based on Statistical Techniques and the other on Engineering Unit Cost Method (46).

Statistical Costs models are based on the relationship between costs and output variables. The relationship could be for a single system over many years or for many different systems over a specified time. In this type of cost model, all the output variables are estimated after examining the actual cost data of the representative system or systems. Lang and Soberman, and Ferreri used this approach in their

costing analysis (32,59).

The costing environment of one system differs from other, so the Statistical Cost approach gives only approximate results. This approach is useful in preliminary planning of facilities that can give a probable costing range.

Nationwide urban transit operating costs for Canada (for many systems) and the OC Transpo operating costs for many years (for one system) are shown in Figure 5.5. The percentage given in Figure 5.5 indicates that more than half of the operating costs go to direct transportation. This is the benefit of operating longer trains that reduce the operating costs. In the following analysis this advantage is evident.

Engineering Unit Costs models are used when a system or its technology is specifically considered. The cost estimate is based on unit costs, so this type of model can be adjusted to variations in costing items. If Unit Costs of various items relating to capital as well as operating costs are known, then the most accurate cost estimate can be obtained by using this approach.

Previously, numerous studies have opted for the unit cost approach in the costing of transit alternatives (6,7,61). But it is not always easy to obtain reliable unit costs for all items. Under these circumstances, a mix of statistical and unit costs approaches are used. Mixed type cost approach has been used in many analyses (46).

A real comparison is possible only if both systems operate in similar environments. The constant and variable assumptions must both be realistic. The actual costing data is preferred to the estimated one. Also the desired comfort level and other vehicle performance factors must be seriously considered. Similar operating

Figure 5.5: Statistical Operating Costs

Source: References 53-60

procedures should be adopted for both systems so that the ability and cost-effectiveness of a system can be weighed and assessed.

5.3.2 Rationale for the Use of Unit Cost Approach

The costing methodology is based on the unit cost approach for two reasons. One, two specific systems (i.e., Transitway and LRT) are the basis of this analysis and both these systems are specified by location. They are both relatively new compared to rail rapid transit and surface bus systems. Only two Transitways are in operation in North America as a full transit system (Ottawa-Carleton and Pittsburgh). The costing data is not mature enough to be used as a base for a statistical approach model.

Secondly, the unit costs for various items are available for the Ottawa-Carleton Transitway and Calgary's LRT (except the operating cost for Calgary LRT system). Calgary Transit does not break down the operating cost data in a similar fashion as to Ottawa-Carleton, Edmonton and Toronto. But after minor adjustments, the data has been put on a unit cost basis.

5.4 Framework Formulation

For the estimation of capital and operating costs including maintenance cost, a general methodology is adopted that is applicable both to Transitway and LRT system. The cost model is shown in Figure 5.6. The capital and operating costs are divided into various components. The total cost varies with the route length and passenger volume. The unit capital and operating costs and the economic life of

Figure 5.6: Cost Model Structure

each item are given in Appendix A and B.

5.4.1 Capital Cost Items

Capital cost for each system is divided into infrastructure, ROW acquisition and vehicles. Infrastructure costs are divided into guideway construction (i.e., Transitway or rail track), and bus garage or yard and shop costs. The ROW acquisition costs are allocated to the system of interest (i.e., Transitway and LRT). Vehicle costs are allocated to standard bus, articulated bus and light rail vehicle (LRV). The guideway construction and ROW acquisition costs of the system are used on a per km basis. Guideway construction and ROW costs are usually combined as a unit in many analyses. But evidence shown in Figures 5.2, 5.3 and 5.4 demonstrates that the Ottawa-Carleton Transitway is cheaper than Calgary's LRT system because of free or very cheap ROW. Therefore, the ROW cost is separated from the total guideway cost in this analysis. For the Ottawa-Carleton Transitway, the guideway construction and property costs are available from Reference (36). For Calgary's LRT system, the ROW cost is extracted by percentage from the study of the South leg of the system. This same percentage is assumed for the rest of the system (34). The vehicle, garage or yard and shop costs are allocated to unit of vehicle. All these unit costs are then discounted at an interest rate of 10% (used by RMOC) on their respective lives. By lowering the discount rate, the LRT's cost recovery costs would be lower. However, for all realistic discount rates, such a sensitivity test is not likely to change conclusions.

5.4.2 Operating Cost Items

Operating costs of urban transit usually consist of period of operation, distance travelled by each vehicle, vehicles scheduled during a certain period, maintenance of route and maintenance and operation of stations.

Operating costs for Transitways are expressed in terms of cost/bus-hour, cost/bus-km and cost/peak schedule bus. Cost of maintenance is allocated on the basis of cost/route-km and cost/station.

Similarly, for LRT systems, the operating costs are estimated as cost/train hour, cost/car-km, cost/peak schedule vehicle, cost/route-km and cost/station.

The main difference in the operating cost for the two systems is the cost/hour. In the case of LRT system, one operator is needed for a train regardless of train length. With the Transitway system, each bus needs one operator. Based on time-related cost, the LRT system is more economical.

5.5 Relative Cost Computations

A real comparison is justified if the alternatives are in the same operating environment. There are a number of urban transit systems in Europe and developing countries that carry more passengers and are cheaper than the North American systems (see Figures 1.2 and 1.3). Similarly, their LRTs (mostly streetcars) have an advantage over North American LRTs in terms of both their ridership and costs. In North America, both Canadian systems (LRT and Transitway) are more cost-effective than U.S. transit systems (see Tables 5.2 and 5.3). The reason is probably the higher ridership. In Canada, the transit ridership is almost three times that of

the U.S. (62,63). Higher ridership is due to the government's strong transit-oriented policies and the concentration of employment in the central core of the cities. Automobiles per household are also slightly less in Canada than the U.S. cities (26,27).

The best comparison can be made of Pittsburgh (U.S.A.) busway and LRT system, since both are operating in the same city. In Ottawa-Carleton the complete system is based on Transitway and can be only compared with LRT systems of Edmonton and Calgary. The Edmonton system is relatively short with only 15% subway and is more expensive than other sites. Therefore, it cannot be compared with the Ottawa-Carleton Transitway. In one case where an underground portion is considered in the CBD for the Ottawa-Carleton Transitway, the unit costs of Edmonton's LRT are used for comparison purposes. The Calgary system, because of its similar length of two-track facility and other features (i.e., the CBD mall, same size of city), will be compared with Ottawa-Carleton Transitway in this analysis.

5.6 Cost Model Algorithm

The algorithms used for cost analysis are shown in Figures 5.7 and 5.8. Figure 5.7 explains the computation steps when service is operated in a similar fashion for both Transitway and LRT systems. Figure 5.8 shows the steps involved in performing cost computations for the Transitway case only, when a mix of express and non-express services is provided and the movement of vehicles is restricted to exclusive ROW. These steps shown in Figure 5.8 are also applicable if integrated services (i.e., door-to-door service) are operated.

Figure 5.7: Algorithm 1 – Computation Procedure for Transitway and LRT Costs

Figure 5.8: Algorithm 2 – Computation Procedure for Transitway Cost

All the relevant data and formulae used in these models are explained in Appendix B and C.

5.6.1 Inputs to Cost Models

Inputs are divided in two different categories: fixed inputs and variable inputs. Fixed inputs are the capital unit costs, operating unit costs, acceleration, deceleration, and maximum speed of the vehicle, station stop time and turnaround time.

The unit capital and operating costs for various items and their respective lives are given in Appendix A and B. The remaining inputs are given in Table 3.3 of Chapter 3.

The variable inputs are the daily passengers, route length, vehicle capacity, number of cars per train, station spacing, trip length and type of service.

5.6.2 Outputs of Cost Models

Outputs are the results of the inputs to the model in combination with other operating data. Services are scheduled for each specified route and passenger volumes. With the provision of daily operating periods, the operating data for one day is determined. This is further converted to yearly based data. The yearly operating data, together with the unit cost inputs, yields the various categories of costs. These output cost variables are shown in Figures 5.7 and 5.8.

5.7 Assumptions Used in Cost Analysis

5.7.1 Common Assumptions

These assumptions are the same for both the Transitway and LRT system unless otherwise stated.

1. Operating Procedure

Both buses and LRVs are operated in a similar fashion. Their movement is restricted to an exclusive facility (i.e., no bus goes to city streets). The vehicles make stops at every station and a two-way service is provided.

In the case of the rapid transit system, the passengers have to reach the rapid transit station by the access/egress system. In this analysis, an identical access/egress system is assumed for both the Transitway and LRT systems. This means that the resulting cost estimates do not include the costs for the access/egress system. The passengers are assumed to be present at station at the time of their departure.

2. Station Spacing

A recent statistical study has divided the North American LRT systems into three groups (35). The first group includes those systems that are relatively longer (e.g., Calgary and San Diego). The average station spacing for this group is 0.9 km. The second group shows systems of shorter lengths. The station spacing of this group is about 0.3 km. The third group (Streetcars) has station spacing of about 0.1 km.

The Ottawa-Carleton Transitway station spacing is about 1 km. As previously stated, the analysis is based on the data from Calgary and Ottawa-Carleton, so station spacing of 1 km is assumed in this analysis.

3. Seats

To keep the same comfort level, the bus seating density is used. Seating capacity considered with other performance factors for buses and LRVs is discussed

in Chapter 3. The schedule design capacity of each individual vehicle with 80% load factor is used in this analysis.

4. Train Length

Downtown on-street operation usually limits the train length to a maximum of 3 cars/train (28,33). In the Ottawa-Carleton study, the train length was limited to 2 cars/train (64). In Calgary, a train of 3 cars is presently operating with a peak hour headway of 300 seconds (13). The station platform length can be extended in the future in order to accommodate a train length of 5 cars. It is not specified whether the train of 5 cars will use the existing CBD route or operate above or below ground. In this analysis, it is assumed that 5 cars/train can be operated on the surface in the CBD areas. The length of the train when no subway is provided in the CBD area is governed by the street pattern, length of each block and topography of the CBD area.

In this analysis, maximum and minimum lengths of trains in the peak period are kept as 5 and 3 cars/train respectively and the length of the train in the off-peak period is in accordance with the number of passengers served (minimum train length of 2 cars).

5. Headways

Previous studies have assumed about 30 trains/hour with the train length of up to 10 cars/train (6,7). Minimum practical frequency of 40 trains/hour is possible in rail rapid transit because of higher speed and sophisticated signals system (25). Calgary's LRT could be operated with a train length of 5 cars with a minimum of 150 seconds headway (13). In North America most rail transit systems are operating

at a headway of 120 to 130 seconds (25).

Because the maximum length of the train is limited to 5 cars in this analysis, a minimum peak period headway of up to 90 seconds (40 trains/hour) is assumed. To keep an upper limit on headways, for both buses and LRT, a maximum headway of 300 seconds is assumed. The off-peak period headways are in accordance with the number of passengers to be served.

6. Acceleration and Deceleration

In urban transit operation, consideration is always given to human comfort. There are always standees in urban transit, so a value that is less than the maximum acceleration/deceleration is desirable (65). This is called service acceleration.

Service acceleration/deceleration rates are used in this analysis both for buses and LRVs. In practice, the same values cannot be maintained throughout the same route. However, for convenience of computations, the values are assumed to be the same throughout the route. These values are given in Table 3.3 of Chapter 3. They were obtained from the Ottawa-Carleton rapid transit study and Calgary's transit technical data (13,40). These values, however, are compared with other suggested guidelines (25).

7. Station Stop Time

Station stop time consists of two parts: vehicle clearance time and the passenger service time. A reasonable value for vehicle clearance time (i.e., conventional bus) is 9 to 20 seconds (28). Passenger service time depends on many factors, such as number of doors per vehicle, door dimensions, fare collection system, platform type and the number of passengers boarding or alighting the vehicle.

Numerous observed values for boarding/alighting of passengers for various door configurations and fare collection systems are well documented (28).

Station stop time decreases as the number of doors in a vehicle and the frequency of vehicles to serve a certain stop increases. In the afternoon rush hour, for conventional buses, less than 15 to 20 seconds of station stop time has been observed (28). In the case of rail transit, due to wider doors and high platforms, a minimum of 10 seconds station stop time is recommended (25).

A high frequency of vehicle use is needed to serve the number of passengers assumed in this analysis so the station stop time is assumed to be minimal. The values used in this analysis are obtained from Reference (64) and given in Table 3.3 of Chapter 3.

8. Turnaround Time

A reasonable turnaround time both for buses and LRVs can be obtained from actual observation. This time period depends mainly on the type of turnaround facility and the operational activities in the station.

Some studies obtained the actual values at the turnaround points and others have assumed a percentage of the total running time of the vehicle (6,7).

Buses usually take a U-turn to turn around or enter the station at one point and exit at other point. This keeps the turnaround time for a bus to a minimum (25). With rail transit, the vehicle has to use the turnaround facility, which usually takes longer. In this analysis, the turnaround times of 300 seconds for LRV and 120 seconds for bus are assumed.

5.7.2. Variable Assumptions

These assumptions are applied equally to both systems but vary for different cases unless otherwise stated.

1. Line Length

As explained above, in North America, the length of LRT systems varies from 8 km to 24 km (taking into account all three groups of the LRT family). The length for Transitways varies from 6 km to 15 km.

In most cases, the individual routes that connect the CBD of the city to outlying areas fall below 15 km. In this analysis three different routes are considered for costing purpose — 6 km, 9 km and 15 km.

2. Passenger Volumes

Rail rapid transit in North America serves 14% to 20% peak hour passengers of the total weekday patronage (6). During 4 hours of a peak period, the rail transit carries about 55% to 60% of the daily volumes. This amounts to 14% to 15% per peak hour (32). For surface buses, 11% in a peak hour of the total daily volume is proposed as a design criterion (25). Transitway and LRT are supposed to serve more volume compared to surface bus system. In 1987, OC Transpo carried 60% of the daily passengers during peak period resulting in 12% for one peak hour. (OC Transpo's peak period operation amounts to 5 hours (53)).

In this analysis, the daily volume is divided in the following manner:

Peak hour passengers = 12% of daily passengers

Midday hour passengers = 4% of daily passengers

Evening hour passengers = 2% of daily passengers

Details regarding daily and yearly operation periods and operating hours in a year are given in Appendix B.

3. Station Capital Cost

The existing stations of Calgary's LRT system can only accommodate 3 cars/train. The total capital cost of the station is divided by the number of cars/train (i.e., 3). This gives the cost of station per car. In this analysis, when the number of cars increases, the station cost is increased by the same ratio. The guideway construction costs, as shown, include existing station capital costs.

In the Ottawa-Carleton rapid transit study, the capacity analysis for Transitway resulted in 218 standard buses per hour, 30% of which are express buses that make no stops at stations (66). The remaining 168 buses stop at the stations. The number shown here is based on the higher LOS criteria of the Ottawa-Carleton transit authorities, otherwise higher hourly number of buses are suggested for Transitway capacity (See Chapter 3).

168 buses per hour can use the 3 berth station, therefore, the cost of the station is divided by the number of berths (i.e., 3) to get the cost per berth. One berth is used by 56 buses (i.e., $168/3$), so for each increment of 56 buses, the cost of station is increased by the same ratio. Care is taken when an articulated bus is used in the analysis. One articulated bus is taken to be equal to one and half standard buses (53).

5.8 Scheduling

The hourly volumes at maximum load point in the peak period are divided by

the train length (number of cars per train) and the number of passengers per car. This gives a frequency of trains per hour that is converted to the frequency of cars per hour. A similar procedure is adopted for midday and evening operations.

Buses do not operate in trains, so the specified volumes (in peak or off peak hour) are divided by the capacity of the individual bus. This gives the number of buses per hour.

These figures were converted into yearly data to obtain the corresponding costs.

5.9 Costing Results

A review of a number of system cost comparisons suggests, at 4,000 passengers per hour, the bus rapid transit system is more cost efficient than the rail rapid transit system. This research did not study the cost efficiency of the bus rapid transit system for 4,000 passengers per hour.

Ottawa-Carleton Transitway, when completed, will carry 15,000 passengers per hour. When the volume exceeds this figure, the CBD portion of the Transitway (or a future rail-based system) will use an underground tunnel (30,51). It is assumed that more than 15,000 peak hour passengers are better served by the use of a tunnel in the CBD area than surface street operations (in mixed traffic or exclusive). In this analysis, passenger volumes of 8,000 and 15,000 are assumed for sensitivity tests.

The cost per passenger-kilometre or per passenger are developed in this analysis. The capital cost per passenger, for various cost components at 8,000 and 15,000 peak hour passenger levels with route lengths of 6 and 15 km for both

Transitway and LRT system are shown in Figures 5.9 and 5.10. The cost efficiency of Transitway is clearly evident from these figures. The Transitway capital cost both for standard and articulated buses is about three times less than the LRT system. The articulated bus is 3% to 4% more expensive than the standard bus at an 8,000 peak hour passenger volume level. When the peak hour passenger volume increases to 15,000, the articulated bus is 5% cheaper than the standard bus for a route length of 6 km and 6% cheaper for a route length of 15 km. This means that operating articulated buses further reduces the capital costs of the Transitway.

The operating cost for all the components are shown in Figures 5.11 and 5.12. Based on the operating cost per passenger, as expected, the LRT system is cheaper than both standard and articulated buses. For a route length of 6 km with peak hour passengers of 8,000, the standard bus is 2.07 times more expensive than the LRT system and the articulated bus is 1.50 times more expensive. Keeping the number of passengers per hour constant (8,000) and increasing the route length to 15 km, the above ratio increases to 2.19 and 1.58 respectively. These ratios show that by increasing route length by 2.5 times and distributing the same passenger volume over a longer route length, the cost per passenger does not increase by the same ratio. When both the route length and peak hour passenger volumes increase to 15 km and 15,000 respectively, this ratio changes to 2.17 and 1.53 times. By comparing Figures 5.11b and 5.12a, one can conclude that at higher volumes the operating cost of the LRT system reduces by 1.03 times and for the standard and articulated bus costs are reduced to 1.05 and 1.07 times respectively. As the route length increases the LRT is less economical in operational terms than the standard and articulated bus.

Figure 5.9: Breakdown of Capital Costs per Pass: 8,000 Pass/hr

Figure 5.10: Breakdown of Capital Costs per Pass: 15,000 Pass/hr

Figure 5.11: Breakdown of Operating Costs per Pass: 8,000 Pass/hr

Figure 5.12: Breakdown of Operating Costs per Pass: 15,000 Pass/hr

This means that operating costs are reduced if a higher number of passengers are carried. The LRT system is, however, operationally cheaper than the Transitway system.

Total costs per passenger for route lengths of 6 km and 15 km with peak hour passenger volumes of 8,000 and 15,000 are shown in Figures 5.13 and 5.14. With a peak hour passenger volume of 8,000 and route length of 6 km, the LRT system is over two times more expensive than the Transitway. As the route length increases to 15 km and the peak hour volume rises to 15,000, the LRT system is about 1.38 times more expensive than the standard bus and 1.70 times more expensive than the articulated bus.

5.10 Sensitivity Tests

In actual practice, North American Transitways are superior to the LRT systems. It is debatable under what circumstances each system is more cost-effective, especially when the actual passenger volumes are far below the suggested design volumes (i.e., the theoretical capacity of the system).

Sensitivity tests at peak hour volumes of 8,000 and 15,000 were carried out to see changes in costs due to variation in selected factors. It is to be noted that the cost for both longer and shorter trains are provided in the respective tables but comparison made in these sensitivity tests is based on longer train only.

5.10.1 Construction Cost Increment

In the case of the Ottawa-Carleton Transitway, it is shown that the construc

Figure 5.13: Breakdown of Total Cost per Pass: 8,000 Pass/hr

Figure 5.14: Breakdown of Total Cost per Pass: 15,000 Pass/hr

tion cost is very low compared to the LRT system of Calgary. This low construction cost is the result of cheaper ROW because most of the ROW was in the government jurisdiction that was used for free or for a nominal cost (64).

In one test the construction and ROW cost is increased by 30% and compared with the LRT's original costs. The results are shown in Tables 5.4 and 5.5. This increase in cost has no significant effect on the total cost of the system. The LRT system is 1.98 times and 1.89 times more expensive on a per passenger basis than the Transitway system using articulated buses for route lengths of 6 and 15 km with a peak hour passenger volume of 8,000. The cost ratio changes to 1.64 and 1.57 times respectively with a peak hour passenger volume of 15,000. Transitway is 12% costlier than the original case. Similar results were obtained for standard bus. The LRT system capital cost, which is about 3 times more than the Transitway cost, is less sensitive to a 30% increase in the Transitway construction cost.

5.10.2 Wage Increase

Since LRT system operates with a number of cars/train, it needs fewer operators than buses. The LRT system with longer trains and fewer operators is supposed to be cheaper than the bus transit system.

The OC Transpo top operator rate in 1976 was \$6.63 per hour. In 1987 it was \$14.03 (53). This shows a 2.12 times increase in 11 years. It is assumed that the same upward trend will continue in the following 15 years. The present operating cost per hour is \$19.80 and it is expected to be 2.85 times higher than the present rate 15 years from now. The 1987 operating costs per hour for both Transitway and

Table 5.4: Cost Summary with Increased Construction Costs: 8,000 Pass/hr

Variables	Standard Bus			Articulated Bus			LRT		
	Capital	Operating	Total	Capital	Operating	Total	Capital	Operating	Total
Route Guideway Length Construction (km) Cost									
6 30% Increase	6	5	11	6	4	10	15(16)	3(2)	18(18)
9 30% Increase	5	5	10	6	3	9	14(15)	2(2)	16(17)
15 30% Increase	5	5	10	6	3	9	14(15)	2(2)	16(17)
							\$ / pass		
6 30% Increase	.33	.29	.62	.34	.21	.55	.89(.95)	.15(.14)	1.04(1.09)
9 30% Increase	.49	.42	.91	.51	.30	.81	1.30(1.37)	.21(.20)	1.51(1.57)
15 30% Increase	.81	.68	1.49	.84	.49	1.33	2.10(2.21)	.34(.31)	2.44(2.52)

Note: . Value inside the bracket for 5 cars/train
. Value outside the bracket for 3 cars/train for 8,000 pass/hr and 4 cars/train at 15,000 pass/hr
. 1987\$

Table 5.5: Cost Summary with Increased Construction Costs: 15,000 pass/hr

Variables	Standard Bus			Cents/Pass-km			LRT
	Route Length (km)	Guideway Construction Cost	Capital Operating Total Capital	Operating Total Capital	Operating Total Capital	Operating Total Capital	
6	30% Increase	4	5	9	4	4	12(12)
9	30% Increase	4	4	8	3	3	11(12)
15	30% Increase	4	4	8	4	3	11(11)
			\$ / pass				
6	30% Increase	.26	.28	.54	.24	.20	.74(.72)
9	30% Increase	.37	.40	.77	.36	.28	1.04(.97)
15	30% Increase	.61	.65	1.26	.58	.46	1.65(1.63)

Note: Same remarks as Table 5.4

LRT systems were increased by the same factor and the results are shown in Tables 5.6 and 5.7.

With an 8,000 peak hour passenger volume and a route length of 6 km, the LRT system is 1.47 and 1.82 times respectively more expensive on a per passenger basis than standard and articulated bus. Even standard and articulated buses are now 33% and 27% more expensive than the original wages level. An increase in route length does not result in any significant changes. By increasing the peak hour passenger volumes to 15,000, this difference becomes minimal. At this volume, the LRT system is 1.07 times more expensive than the standard bus and 1.43 times more expensive than the articulated bus. The potential of articulated bus compared to standard bus is evident. Even following an increase in the route length to 15 km, the LRT system is still 1.04 and 1.37 times respectively more expensive than standard and articulated buses for a peak hour passenger volume of 15,000. The LRT system operator wages at 1987 level and the standard bus operator wages at 2002 level, for 15,000 peak hour passengers and a 15 km route length, give equal results. But for 8,000 peak hour passengers, the standard bus is still cheaper. This means that at higher wages level and for a longer period than 15 years, the comparison of LRT system and standard buses may give some significance over each other. The articulated bus is believed to be still cost-effective due to the big difference shown above.

5.10.3 Route Length

Route length is changed and resulting costs are determined. Route lengths

Table 5.6: Cost Summary with Increased Operator Wages: 8,000 Pass/hr

Route Length (km)	Operator Wages	Cents/Pass-km								
		Standard Bus			Articulated Bus					
		Capital	Operating	Total	Capital	Operating	Total			
6	1987	5	5	10	5	4	9	15(16)	3(2)	18(18)
	2002	5	8	13	5	6	11	15(16)	3(3)	18(19)
	1987	4	5	9	5	3	8	14(15)	2(2)	16(17)
9	2002	5	8	13	5	5	10	14(15)	3(3)	17(18)
	1987	4	5	9	5	3	8	14(15)	2(2)	16(17)
	2002	4	8	12	5	5	10	14(15)	3(3)	17(18)
6	1987	.27	.29	.56	.28	.21	.49	.89(.95)	.15(.14)	1.04(1.09)
	2002	.27	.50	.77	.28	.34	.62	.89(.95)	.22(.18)	1.11(1.13)
	1987	.40	.42	.82	.42	.30	.72	1.30(1.37)	.21(.20)	1.51(1.57)
9	2002	.40	.71	1.11	.42	.48	.90	1.30(1.37)	.30(.25)	1.60(1.62)
	1987	.65	.68	1.33	.68	.49	1.17	2.10(2.21)	.34(.31)	2.44(2.52)
	2002	.65	1.14	1.79	.68	.77	1.45	2.10(2.21)	.47(.39)	2.57(2.60)

Table 5.7: Cost Summary with Increase Operator Wages: 15,000 Pass/hr

Route Length (km)	Variables	Cents/pass-km									
		Standard Bus					Articulated Bus				
	Operator Wages	Capital	Operating	Total	Capital	Operating	Total	Capital	Operating	Total	LRT
6	1987	4	5	9	3	3	6	10(10)	2(2)	12(12)	
	2002	4	8	12	3	5	8	10(10)	3(3)	13(13)	
	1987	4	4	8	3	3	6	9(10)	2(2)	11(12)	
9	2002	4	8	12	3	5	8	9(10)	3(2)	12(12)	
	1987	4	4	8	3	3	6	9(9)	2(2)	11(11)	
	2002	4	7	11	3	5	8	9(9)	3(2)	12(11)	
6	1987	.22	.28	.50	.21	.20	.41	.60(.59)	.14(.13)	.74(.72)	
	2002	.22	.49	.71	.21	.32	.53	.60(.59)	.19(.17)	.79(.76)	
	1987	.32	.40	.72	.31	.28	.59	.85(.80)	.19(.17)	1.04(.97)	
9	2002	.32	.69	1.01	.31	.46	.77	.85(.80)	.26(.24)	1.11(1.04)	
	1987	.53	.65	1.18	.50	.46	.96	1.35(1.33)	.30(.30)	1.65(1.63)	
	2002	.53	1.11	1.64	.50	.74	1.24	1.35(1.33)	.40(.37)	1.75(1.70)	

\$/Pass

Note: Same remarks as Table 5.4

of 6, 9 and 15 km are used in the analysis.

The LRT system is capital intensive. It is seen in these sensitivity tests that at lower volumes (8,000 peak hour passengers), the LRT system is two times more expensive than the Transitway system. But, as the passenger volumes increase, the cost differences narrow.

This indicates that for dense corridors where potential riders are available, the LRT system is the more suitable technology. It is better suited for higher volumes and short routes that reduce the capital cost and thus the total costs. At a peak hour passenger volume of 8,000 with route length of 15 km, the cost per passenger is 42% and 43% more for standard bus, articulated bus and LRT system respectively compared with the cost per passenger for 6 km route length. But when the passenger volume increases to 15,000, the above percentage becomes 42%, 43% and 47% respectively. This comparison shows that LRT system is more sensitive to changes in route length. The reason is the higher costs for infrastructure and vehicles. The results in various tables indicate that with an increase of passenger volume and route length, the reduction in costs for the LRT system and articulated bus is double that of standard bus.

5.10.4 Station Spacing

The station spacing is increased by half a kilometre for both the Transitway and LRT systems. By increasing station spacing, the average overall speed increases and the corresponding cycle time drops. In turn this reduces the fleet size and the operating costs. Both the capital and operating costs are reduced to some extent but

no significant gain for one system over the other is shown. The results are shown in Tables 5.8 and 5.9. Increasing station spacing even further might favour one system over the other.

5.10.5 Change in Peak Period

Cost calculations are carried out for a case where the peak hour period is reduced from five hour duration to four hours. The results are shown in Tables 5.10 and 5.11. Both capital and operating costs increase due to reduced vehicle-hours and vehicle-kilometres.

At an 8,000 peak hour passenger volume level with the route length of 6 km, the LRT system, standard bus and articulated bus become 1.07, 1.08 and 1.05 times more expensive than the original case. With the increase in route length, the above ratios are 1.08, 1.09 and 1.06 respectively. This shows that with the increase in route length, both Transitway and LRT systems are equally effected. The same effect is seen when passenger volume is increased.

5.10.6 Changes in Load Factor

In one sensitivity test, vehicles were operated at 100% load factor (i.e., design capacity). The results shown in Tables 5.12 and 5.13 indicate that the standard bus, articulated bus and LRT system all became more expensive in terms of capital costs and cheaper in terms of operating costs. At low and high volume levels and for short and long route lengths, all the modes benefited uniformly. For higher volumes all systems became a little bit more economical compared to lower volumes. At original

Table 5.8: Cost Summary with Increased Station Spacing: 8,000 Pass/hr

		<u>Cents/Pass-km</u>									
<u>Variables</u>		<u>Standard Bus</u>					<u>Articulated Bus</u>				
Route Station											
Length Spacing		Capital	Operating	Total	Capital	Operating	Total	Capital	Operating	Total	
(km)											
6	1	5	5	10	5	4	9	15(16)	3(2)	18(18)	
	1.5	4	5	9	5	3	8	15(15)	2(2)	17(17)	
	1	4	5	9	5	3	8	14(15)	2(2)	16(17)	
9	1.5	4	4	8	4	3	7	14(15)	2(2)	16(17)	
	1	4	5	9	5	3	8	14(15)	2(2)	16(17)	
15	1.5	4	4	8	4	3	7	14(14)	2(2)	16(16)	
		<u>\$/Pass</u>									
6	1	.27	.29	.56	.28	.21	.49	.89(.95)	.15(.14)	1.04(1.09)	
	1.5	.26	.26	.52	.27	.19	.46	.87(.91)	.14(.13)	1.01(1.04)	
	1	.40	.42	.82	.42	.30	.72	1.30(1.37)	.21(.20)	1.51(1.57)	
9	1.5	.38	.38	.76	.40	.28	.68	1.26(1.32)	.20(.18)	1.46(1.50)	
	1	.65	.68	1.33	.68	.49	1.17	2.10(2.21)	.34(.31)	2.44(2.52)	
15	1.5	.63	.61	1.24	.66	.45	1.10	2.05(2.13)	.32(.29)	2.37(2.42)	

Note: Same remarks as Table 5.4

Table 5.9: Cost Summary with Increased Station Spacing: 15,000 Pass/hr

Variables		Cents/Pass-km				Articulated Bus		LRT		
		Standard Bus		Articulated Bus						
Route	Station	Capital	Operating	Total	Capital	Operating	Total	Capital	Operating	Total
Length	Spacing									
(km)										
6	1	4	5	9	3	3	6	10(10)	2(2)	12(12)
	1.5	3	4	7	3	3	6	9(10)	2(2)	11(12)
	1	4	4	8	3	3	6	9(10)	2(2)	11(12)
9	1.5	3	4	7	3	3	6	9(9)	2(2)	11(11)
	1	4	4	8	3	3	6	9(9)	2(2)	11(11)
15	1.5	3	4	7	3	3	6	9(9)	2(2)	11(11)
6	1	.22	.28	.50	.21	.20	.41	.60(.59)	.14(.13)	.74(.72)
	1.5	.20	.25	.45	.19	.18	.37	.57(.56)	.13(.12)	.70(.68)
	1	.32	.40	.72	.31	.28	.59	.85(.80)	.19(.17)	1.04(.97)
9	1.5	.29	.36	.65	.28	.26	.54	.81(.83)	.18(.18)	.99(1.01)
	1	.53	.65	1.13	.50	.46	.96	1.35(1.33)	.30(.30)	1.65(1.63)
15	1.5	.47	.58	1.05	.45	.42	.87	1.30(1.27)	.28(.27)	1.58(1.54)

Note: Same remarks as Table 5.4

Table 5.10: Cost Summary with Reduced Peak Period: 8,000 Pass/hr

<u>Variables</u>		<u>Cents/Pass-km</u>				<u>\$/Pass</u>			
		<u>Standard Bus</u>		<u>Articulated Bus</u>		<u>LRT</u>			
Route Length (km)	Daily Service	Capital	Operating	Total Capital	Operating	Total Capital	Operating	Total	
6	5 Pk.hr	5	5	10	5	4	9	15(16)	3(2)
	4 Pk.hr	5	5	10	5	4	9	16(17)	3(2)
	5 Pk.hr	4	5	9	5	3	8	14(15)	2(2)
9	4 Pk.hr	5	5	10	5	4	9	16(17)	2(2)
	5 Pk.hr	4	5	9	5	3	8	14(15)	2(2)
	4 Pk.hr	5	5	10	5	4	9	16(17)	2(2)
15	5 Pk.hr	4	5	9	5	3	8	14(15)	2(2)
	4 Pk.hr	5	5	10	5	3	8	15(16)	2(2)
	4 Pk.hr	5	5	10	5	3	8	15(16)	2(2)
6	5 Pk.hr	.27	.29	.56	.28	.21	.49	.89(.95)	.15(.14)
	4 Pk.hr	.29	.30	.59	.31	.22	.53	.97(1.03)	.16(.14)
	5 Pk.hr	.40	.42	.82	.42	.30	.72	1.30(1.37)	.21(.20)
9	4 Pk.hr	.43	.43	.86	.45	.31	.76	1.41(1.48)	.22(.20)
	5 Pk.hr	.65	.68	1.33	.68	.49	1.17	2.10(2.21)	.34(.31)
	4 Pk.hr	.71	.70	1.41	.74	.51	1.25	2.28(2.41)	.35(.32)

Note Same remarks as Table 5.4

Table 5.11: Cost Summary with Reduced Peak Period: 15,000 Pass/hr
Cents/Pass-km

<u>Variables</u>		<u>Standard Bus</u>			<u>Articulated Bus</u>			<u>LRT</u>	
Route Length (km)	Daily Service	Capital	Operating	Total	Capital	Operating	Total	Capital	Operating
6	5 Pk.hr	4	5	9	3	3	6	10(10)	2(2)
	4 Pk.hr	4	5	9	4	3	7	11(11)	2(2)
	5 Pk.hr	4	4	8	3	3	6	9(10)	2(2)
9	4 Pk.hr	4	5	9	4	3	7	10(11)	2(2)
	5 Pk.hr	4	4	8	3	3	6	9(9)	2(2)
15	4 Pk.hr	4	4	8	4	3	7	10(10)	2(2)
	5 Pk.hr	4	5	9	4	3	7	10(10)	2(2)
<u>\$/Pass</u>									
6	5 Pk.hr	.22	.28	.50	.21	.20	.41	.60(.59)	.14(.13)
	4 Pk.hr	.24	.28	.52	.23	.20	.43	.65(.66)	.14(.13)
	5 Pk.hr	.32	.40	.72	.31	.28	.59	.85(.80)	.19(.17)
9	4 Pk.hr	.35	.41	.76	.33	.29	.62	.92(.95)	.20(.19)
	5 Pk.hr	.53	.65	1.18	.50	.46	.96	1.35(1.33)	.30(.30)
15	4 Pk.hr	.57	.66	1.23	.54	.47	1.01	1.47(1.51)	.31(.30)
	5 Pk.hr								
									1.78(1.81)

Note Same remarks as Table 5.4

Table 5.12: Cost Summary with Increased Load Factor: 8,000 Pass/hr

Variables		Cents/Pass-km									
		Standard Bus					Articulated Bus				
Route Length (km)	Load Factor	Capital	Operating	Total	Capital	Operating	Total	Capital	Operating	Total	
6	80%	5	5	10	5	4	9	15(16)	3(2)	18(18)	
	100%	5	4	9	5	3	8	14(15)	2(2)	16(17)	
	80%	4	5	9	5	3	8	14(15)	2(2)	16(17)	
9	100%	5	4	9	5	3	8	14(14)	2(2)	16(16)	
	80%	4	5	9	5	3	8	14(15)	2(2)	16(17)	
15	100%	5	3	8	5	3	8	13(14)	2(2)	15(16)	
<hr/>											
		\$/Pass									
6	80%	.27	.29	.56	.28	.21	.49	.89(.95)	.15(.14)	1.04(1.09)	
	100%	.28	.25	.53	.29	.18	.47	.85(.87)	.13(.12)	.98(.99)	
	80%	.40	.42	.82	.42	.30	.72	1.30(1.37)	.21(.20)	1.51(1.57)	
9	100%	.41	.36	.77	.43	.26	.69	1.23(1.27)	.18(.17)	1.41(1.44)	
	80%	.65	.68	1.33	.68	.49	1.17	2.10(2.21)	.34(.31)	2.44(2.52)	
15	100%	.68	.58	1.26	.71	.42	1.13	2.01(2.07)	.28(.26)	2.29(2.33)	

Note Same remarks as Table 5.4

Table 5.13: Cost Summary with Increased Load Factor: 15,000 Pass/hr

		<u>Cents/Pass-km</u>									
<u>Variables</u>		<u>Standard Bus</u>					<u>Articulated Bus</u>				
											<u>LRT</u>
Route Length (km)	Load Factor	Capital	Operating	Total	Capital	Operating	Total	Capital	Operating	Total	
6	80%	4	5	9	3	3	6	10(10)	2(2)	12(12)	
	100%	3	4	7	3	3	6	9(9)	2(2)	11(11)	
	80%	4	4	8	3	3	6	9(10)	2(2)	11(12)	
9	100%	3	4	7	3	3	6	9(9)	2(2)	11(11)	
	80%	4	4	8	3	3	6	9(9)	2(2)	11(11)	
15	100%	3	4	7	3	2	5	8(8)	2(2)	10(10)	
		<u>\$/Pass</u>									
6	80%	.22	.28	.50	.21	.20	.41	.60(.59)	.14(.13)	.72(.72)	
	100%	.20	.23	.43	.19	.16	.35	.54(.54)	.12(.11)	.66(.65)	
	80%	.32	.40	.72	.31	.28	.59	.85(.80)	.19(.17)	1.04(.97)	
9	100%	.29	.34	.63	.26	.23	.61	.77(.77)	.16(.15)	.93(.92)	
	80%	.53	.65	1.18	.50	.46	.96	1.35(1.33)	.30(.30)	1.65(1.63)	
15	100%	.48	.54	1.02	.46	.37	.83	1.24(1.24)	.26(.24)	1.50(1.48)	

Note: Same remarks as Table 5.4

load factor for a 15 km route length with an 8,000 peak hour passengers volume the LRT system is 2.15 times more expensive than the articulated bus. By increasing the load factor, this multiplier becomes 2.06. (LRT system becomes 4% cheaper by increasing load factor.) As both the route length and passenger volumes increase, the articulated bus now becomes 1.78 times more expensive. The LRT system cost-efficiency drops as the route length and passenger volumes increase. The reason is the similar increase in load factor which gives more benefit to articulated bus. From the increase in peak hour passenger volume and load factor, the articulated bus cost per passenger drops by 12% and the LRT system costs drop by 2% only. The standard bus also gets some benefits but is dominated by the articulated bus both in terms of capital and operating costs.

5.10.7 Turnaround Time

Tables 5.14 and 5.15 show the results of analysis for changes in turnaround time. The original analysis is based on 120 and 300 seconds turnaround time for buses and LRT system respectively. In this test, these values are interchanged. Given an 8,000 peak hour volume with a 6 km route length, the Transitway becomes 1.10 times more expensive. But when the route length increases, this disadvantage of Transitway system drops to 1.03 times. At higher volumes, there is no significant change. It is concluded here that the shorter turnaround time gives some benefit to LRT system for shorter route lengths but for the longer route length, this advantage of LRT system disappears.

Table 5.14: Cost Summary with Varying Turnaround Time: 8,000 Pass/hr

<u>Variables</u>		<u>Cents/Pass-km</u>									
		<u>Standard Bus</u>					<u>Articulated Bus</u>				
Route	Turnaround	Capital	Operating	Total	Capital	Operating	Total	Capital	Operating	Total	LRT
Length	Time										
(km)	(sec)										
6	300	5	5	10	5	4	9	14(15)	2(2)	16(17)	
	120	5	6	11	5	3	8	15(16)	3(2)	18(18)	
	300	5	5	10	5	3	8	14(15)	2(2)	16(17)	
9	120	3	5	8	5	4	9	14(15)	2(2)	16(17)	
	300	4	5	9	5	3	8	14(14)	2(2)	16(16)	
	120	3	5	8	5	4	9	14(15)	2(2)	16(17)	
15	300	3	5	8	5	4	9	14(15)	2(2)	16(17)	
	120	3	5	8	5	4	9	14(15)	2(2)	16(17)	
		<u>\$/Pass</u>									
6	300	.27	.29	.56	.28	.21	.49	.84(.89)	.14(.12)	.98(1.01)	
	120	.29	.34	.63	.30	.24	.54	.89(.95)	.15(.14)	1.04(1.09)	
	300	.40	.42	.82	.42	.30	.72	1.24(1.31)	.20(.18)	1.44(1.49)	
9	120	.41	.47	.88	.44	.33	.77	1.30(1.37)	.21(.20)	1.51(1.57)	
	300	.65	.68	1.33	.68	.49	1.17	2.04(2.16)	.32(.30)	2.36(2.46)	
	120	.67	.73	1.40	.70	.52	1.22	2.10(2.21)	.34(.31)	2.44(2.52)	

Table 5.15: Cost Summary with Varying Turnaround Time: 15,000 Pass/hr

		<u>Cents/Pass-km</u>										
<u>Variables</u>		<u>Standard Bus</u>					<u>Articulated Bus</u>					<u>LRT</u>
Route Turnaround Length Time (km) (sec)		Capital Operating		Total		Capital Operating	Total		Capital Operating	Total		
6	300	4	5	9	3	3	6	9(9)	2(2)	11(11)		
	120	4	5	9	4	4	8	10(10)	2(2)	12(12)		
	300	4	4	8	3	3	6	9(9)	2(2)	11(11)		
9	120	4	5	9	4	3	7	9(10)	2(2)	11(12)		
	300	4	4	8	3	3	6	9(9)	2(2)	11(11)		
15	120	4	5	9	5	5	10	9(9)	2(2)	11(11)		
<u>\$/Pass</u>												
6	300	22	.28	.50	.21	.20	.41	.54(.53)	.12(.12)	.66(.65)		
	120	.24	.33	.57	.23	.23	.46	.60(.59)	.14(.13)	.79(.79)		
	300	.32	.40	.72	.31	.28	.59	.80(.78)	.18(.17)	.98(.95)		
9	120	.34	.45	.79	.33	.31	.64	.85(.80)	.19(.17)	1.04(.97)		
	300	.53	.65	1.18	.50	.46	.96	1.30(1.27)	.28(.28)	1.58(1.55)		
15	120	.54	.69	1.23	.49	.49	.98	1.35(1.33)	.30(.30)	1.65(1.63)		

5.10.8 Deduction in Patronage

It is assumed that the forecasted patronage for which the capital expenditures have been estimated falls short by 35%. The results are shown in Tables 5.16 and 5.17. Both capital and operating costs increased by a significant amount. In all cases, the impact on the LRT system is 3% to 5% higher than the Transitway. Each system is more expensive (one and half times more) than the original estimates. From these results, one can conclude that a higher patronage is necessary to justify the higher capital expenditures.

5.10.9 Express and Non-Express Service

In this sensitivity test, a mix of express and non-express service is considered. The movement of vehicles is restricted to exclusive facility only. The route lengths and passenger volumes are the same as for other tests. Both standard and articulated buses are included. The results are shown in Tables 5.18 and 5.19. Both capital and operating costs are reduced. Operationally, standard bus becomes about 50% cheaper and articulated bus becomes 60% cheaper. As the route length increases, the cost advantage of this service decreases somewhat. Starting from the base in which the time advantage for express service over non-express service is fixed (i.e., 10 minutes), an increase in time advantage and the route length will result in a similar cost advantage for short routes.

At 8,000 peak hour passenger level, for all routes lengths, the LRT system is still operationally cheaper than the standard bus but more expensive than the articulated bus. At 15,000 peak hour passenger volume level, the LRT system and

Table 5.16: Cost Summary with Reduced Patronage: 8,000 Pass/hr

Route Length (km)	Variables Reduced	\$/Pass-km						
		Standard Bus			Articulated Bus			LRT
		Capital	Operating	Total	Capital	Operating	Total	
6	Actual	.05	.05	.10	.05	.04	.09	.15(.16)
	35% Reduced	.07	.08	.15	.07	.05	.12	.23(.24)
	Actual	.04	.05	.09	.05	.03	.08	.14(.15)
9	35% Reduced	.07	.07	.14	.07	.05	.12	.22(.23)
	Actual	.04	.05	.09	.05	.03	.08	.14(.15)
	35% Reduced	.07	.07	.14	.07	.05	.12	.22(.23)
15	Actual	.05	.05	.10	.05	.04	.09	.15(.16)
	35% Reduced	.07	.08	.15	.07	.05	.12	.23(.24)
	Actual	.04	.05	.09	.05	.03	.08	.14(.15)
6	Actual	.27	.29	.56	.28	.21	.49	.89(.95)
	35% Reduced	.41	.45	.86	.43	.32	.75	1.38(1.46)
	Actual	.40	.42	.82	.42	.30	.72	1.30(1.37)
9	35% Reduced	.61	.65	1.26	.64	.47	1.11	1.99(2.11)
	Actual	.65	.68	1.33	.68	.49	1.17	2.10(2.21)
	35% Reduced	1.00	1.05	2.05	1.05	.76	1.81	3.23(3.41)
15	Actual	.27	.29	.56	.28	.21	.49	.89(.95)
	35% Reduced	.41	.45	.86	.43	.32	.75	1.38(1.46)
	Actual	.40	.42	.82	.42	.30	.72	1.30(1.37)
6	35% Reduced	.61	.65	1.26	.64	.47	1.11	1.99(2.11)
	Actual	.65	.68	1.33	.68	.49	1.17	2.10(2.21)
	35% Reduced	1.00	1.05	2.05	1.05	.76	1.81	3.23(3.41)
9	Actual	.27	.29	.56	.28	.21	.49	.89(.95)
	35% Reduced	.41	.45	.86	.43	.32	.75	1.38(1.46)
	Actual	.40	.42	.82	.42	.30	.72	1.30(1.37)
15	35% Reduced	.61	.65	1.26	.64	.47	1.11	1.99(2.11)
	Actual	.65	.68	1.33	.68	.49	1.17	2.10(2.21)
	35% Reduced	1.00	1.05	2.05	1.05	.76	1.81	3.23(3.41)
6	Actual	.27	.29	.56	.28	.21	.49	.89(.95)
	35% Reduced	.41	.45	.86	.43	.32	.75	1.38(1.46)
	Actual	.40	.42	.82	.42	.30	.72	1.30(1.37)
9	35% Reduced	.61	.65	1.26	.64	.47	1.11	1.99(2.11)
	Actual	.65	.68	1.33	.68	.49	1.17	2.10(2.21)
	35% Reduced	1.00	1.05	2.05	1.05	.76	1.81	3.23(3.41)
15	Actual	.27	.29	.56	.28	.21	.49	.89(.95)
	35% Reduced	.41	.45	.86	.43	.32	.75	1.38(1.46)
	Actual	.40	.42	.82	.42	.30	.72	1.30(1.37)
6	35% Reduced	.61	.65	1.26	.64	.47	1.11	1.99(2.11)
	Actual	.65	.68	1.33	.68	.49	1.17	2.10(2.21)
	35% Reduced	1.00	1.05	2.05	1.05	.76	1.81	3.23(3.41)
9	Actual	.27	.29	.56	.28	.21	.49	.89(.95)
	35% Reduced	.41	.45	.86	.43	.32	.75	1.38(1.46)
	Actual	.40	.42	.82	.42	.30	.72	1.30(1.37)
15	35% Reduced	.61	.65	1.26	.64	.47	1.11	1.99(2.11)
	Actual	.65	.68	1.33	.68	.49	1.17	2.10(2.21)
	35% Reduced	1.00	1.05	2.05	1.05	.76	1.81	3.23(3.41)

Note: Same remarks as Table 5.4

Table 5.18: Cost Summary with Express and Non-Express Services: 8,000 Pass/hr

Variables		Cents/Pass-km				
		Standard Bus		Articulated Bus		
Route Length (km)	Express & Non-Express Service	Capital	Operating	Total	Capital	Operating Total
6	a	5	5	10	5	4
	b	4	3	7	5	2
	a	4	5	9	5	3
9	b	4	3	7	5	2
	a	4	5	9	5	3
	b	4	3	7	5	2
15	a	4	5	9	5	3
	b	4	3	7	5	2
		\$/Pass				
6	a	.27	.29	.56	.28	.21
	b	.26	.19	.45	.27	.13
	a	.40	.42	.82	.42	.30
9	b	.39	.28	.67	.41	.18
	a	.65	.68	1.33	.68	.49
	b	.65	.44	1.09	.67	.30
15	a	.65	.44	1.09	.67	.30
	b	.65	.44	1.09	.67	.30
	a	.65	.44	1.09	.67	.30

Note: a = Non-Express service
b = A Mix of Express & Non-Express service
1987\$

Table 5.19: Cost Summary with Express and Non-Express Services: 15,000 Pass/hr

Variables		Cents/Pass-km			
		Standard Bus		Articulated Bus	
Route Length (km)	Express & Non-Express Service	Capital	Operating Total	Capital	Operating Total
6	a	4	5 9	3	3 6
	b	4	3 7	3	2 5
	a	4	4 8	3	3 6
9	b	4	3 7	3	2 5
	a	4	4 8	3	3 6
15	b	3	3 6	3	2 5
			\$/Pass		
6	a	.22	.28 .50	.21	.20 .41
	b	.22	.18 .40	.18	.12 .30
	a	.32	.40 .72	.31	.28 .59
9	b	.32	.26 .58	.26	.16 .43
	a	.53	.65 1.18	.50	.46 .96
15	b	.40	.52 .92	.43	.26 .69

Note: a = Non-Express service
 b = A Mix of Express & Non-Express Service
 1987\$

the standard bus costs equal at route lengths of 6 km and 9 km. At 15 km, the LRT system is cheaper. This indicates that with a 15 km route length, the 10 minute time advantage for express service is not sufficient. The articulated bus is still cheaper than the LRT system. This test shows that the provision of more than one service at one time reduces the capital and operating costs and decreases travel time for some passengers. All the assumptions and related data regarding both express and non-express service are described in Chapter 4 and Appendix C.

5.10.10 Integrated service

The details regarding this type of service are given in Appendix C (Case 3). Based on that procedure, the results for peak hour passenger volumes of 8,000 and 15,000 are shown in Tables 5.20, 5.21, 5.22 and 5.23. At an 8,000 peak hour passenger level, regardless of the route length, the Transitway services are cheaper (about 2 times) than the LRT system. The capital cost advantage of Transitway services is about 3 times than the LRT/standard bus system. Operationally the LRT system is still cheaper than standard bus but is more expensive than articulated bus. If the above comparison is made for LRT/articulated bus system, the standard bus is quite expensive operationally while articulated bus is expensive at a margin. Similar results are obtained for 15,000 peak hour passengers also. These conclusions are based on the individual cost computations for the LRT system, feeder service and connecting service, which gives higher figures for passenger-km and passengers per year. Also the feeder and connecting services are cheaper due to shorter routes and higher passenger volumes. If number of passenger-km or passengers are the same

Table 5.20: Cost Summary for Transitway and LRT/Standard Bus Integrated Service: 8,000 pass/hr

Variables			Standard Bus		Articulated Bus		LRT	
FRL (km)	RRL (km)	CRL (km)	Capital	Operating Total	Capital	Operating Total	Capital	Operating Total
4	6	3	3	5	3	3	13(13)	17(17)
4	9	3	3	5	3	6	12(13)	17(17)
\$/Pass								
4	6	3	.35	.64	.99	.84	1.01(1.07)	.61(.60)
4	9	3	.48	.77	1.25	1.06	1.42(1.47)	.67(.66)
							1.62(1.67)	2.09(2.13)

Note:

```

FRL = Feeder route length
RRL = Rapid transit route length
CRL = CBD area route length
* = Same remarks as Table 4.5

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**Table 5.21: Cost Summary for Transitway and LRT/Articulated Bus
Integrated Service: 8,000 pass/hr**

Variables		Cents/Pass-km				LRT	
		Standard Bus		Articulated Bus		Operating	Total
FRL (km)	RRL (km)	Capital	Operating	Capital	Operating	Capital	Operating
4	6	3	5	3	3	15(15)	11(11)
4	9	3	5	3	3	14(15)	11(11)
				\$/Pass			
4	6	.35	.64	.39	.45	1.04(1.10)	.44(.43)
4	9	.48	.77	.52	.54	1.45(1.52)	.50(.49)
				.99	.84	1.48(1.53)	1.48(1.53)
				1.25	1.06	1.95(2.01)	1.95(2.01)

Note: Same remarks as Table 5.20

Table 5.22: Cost Summary for Transitway and LRT/Standard Bus Integrated Service: 15,000 Pass/hr

[illegible]

Note: Same remarks as Table 5.20

**Table 5.23: Cost Summary for Transitway and LRT/Articulated Bus
Integrated Service: 15,000 Pass/hr**

Variables			Cents/pass-km									
			Standard Bus			Articulated Bus			LRT			
			FRL (km)	RRL (km)	CRL (km)	Capital	Operating	Total	Capital	Operating	Total	Capital
4	6	3	2	4	6	2	3	5	15(15)	17(17)	32(32)	
4	9	3	2	5	7	2	3	5	14(15)	17(17)	31(32)	
			\$/Pass									
4	6	3	.26	.63	.89	.29	.44	.73	.75(.71)	.43(.59)	1.18(1.30)	
4	9	3	.33	.75	1.08	.37	.52	.89	1.00(.95)	.48(.46)	1.48(1.41)	

Note: Same remarks as Table 5.20

to the Transitway then LRT system will be too expensive than Transitway system.

Additionally, if a mix of express and non-express services are operated, the Transitway will give operating benefits similar to those shown in the preceding sub section.

5.11 Cost Analysis Including Subway in CBD Area

Presently OC Transpo is carrying about 13,000 peak hour passengers on Slater and Albert streets (CBD) with an average observed speed of 14 km/h to 24 km/h. These are the highest observed figures for transit systems of the same kind in North America (67). The regional authorities are predicting that in the future, this portion of the Transitway will become saturated and they will have to seek other alternatives (e.g., bus or LRT subway). They have also predicted that OC Transpo will then be able to carry 16,000 peak hour passengers, offer faster speed and incur less operating costs.

The operation of the LRT system, using a subway in the CBD area with the assumption of 40 trains/hour and 6 cars/train, can carry 28,000 passengers/hour. The capacity of one car is 117 passengers. The results, based on the assumptions shown in Appendix C (Case 5) for passenger volumes of 16,000 to 28,000, in a peak hour are shown in Table 5.24.

On a per passenger basis, the results indicate that at a peak hour passenger volume of 16,000, the standard bus is 3% more expensive than the LRT system. At 19,000 passenger level both are equal. At a peak hour passenger volume of 24,000 the standard bus is 4% cheaper than the LRT system. At a 28,000 peak hour

Table 5.24: Cost Summary: Including Subway in CBD Area

Variables	Standard Bus		Articulated Bus		LRT	
	Capital	Operating Total	Capital	Operating Total	Capital	Operating Total
Pass/hr						
16,000	.11(1.18)	.05(.50)	.11(1.21)	.03(.36)	.10(1.02)	.06(.61)
19,000	.10(1.05)	.05(.50)	.10(1.07)	.03(.36)	.09(.95)	.06(.59)
24,000	.08(.85)	.05(.49)	.08(.88)	.03(.35)	.08(.83)	.05(.56)
28,000	.07(.75)	.05(.48)	.07(.77)	.03(.34)	.07(.77)	.05(.54)

Note

- i) Value outside the bracket: \$/Pass km
- ii) Value inside the bracket: \$/Pass
- iii) Route length = 10.5 km
- iv) 6 cars/train
- v) 1987\$

passenger volume, the standard bus is 6% cheaper than the LRT system. At either volume levels, the articulated bus is cheaper by a higher margin.

The comparative cost analysis in the preceding sections indicates that the LRT system can operationally compete with the Transitway only when the Transitway services are designed in a fashion similar to the LRT system. When a mix of express and non-express service, integrated services and subway operation are included in the analysis, the Transitway shows cost-superiority both in terms of capital and operating costs. However, all services of the Transitway are cost-efficient when the comparison is made on total cost per passenger basis. Additionally, the results favour Transitway when low volumes and longer routes are assumed. The results will be more favourable to the Transitway if the operational flexibility of buses is taken into account (e.g., turning buses back at some stations or at each station, and skip-stop services). The above analysis also indicates that due to less capital cost of Transitway than with LRT system, Transitway can be built shorter and serve the same purpose as that of LRT system or can be built longer than LRT system with the same capital costs and thus securing more ROW in early stages.

CHAPTER 6

COST-EFFECTIVENESS OF TRANSITWAY AND LRT SYSTEMS

6.1 The Theory of Cost-Effectiveness

The term cost-effectiveness is an aggregate of two words — "cost" and "effectiveness". The cost-effectiveness analysis is defined as a designed analytical study which assists decision-makers in identifying a preferred alternative (68). In cost-effectiveness analysis, all the involved factors in the evaluation of the alternatives are divided into two groups: cost and evaluation criteria (measure of effectiveness). The final selection of any alternative is based on two different information items rather than one single value. This differentiates cost-effectiveness analysis from cost-benefit analysis. In cost-benefit analysis, the evaluation of alternatives results in costs and benefits (that can be quantified in dollar terms) without showing their overall consequences (69).

Cost-effectiveness analysis has been in use for a long time. Over time, it has been refined to some extent. Many researchers incorporated probability and utility theories in cost-effectiveness analysis in order to refine the results of their analysis. Usually, evaluation criteria are ranked according to their desirability. The ranks are then converted into weights and the various effectiveness measures are estimated. Then all the costs and the achieved measures of effectiveness are put forward to the decision-makers.

Since decision-makers frequently make their choices upon objective as well as subjective criteria, the cost-effectiveness analysis is a helpful tool for decision-

makers. Cost-effectiveness analysis by itself does not make the process of decision-making easy, but it improves the quality of the decision (70).

6.2 Cost-Effectiveness Comparisons

In urban transit, the evaluation criteria and their numbers vary from one location to another. In the case of Calgary's LRT South corridor, the evaluation criteria taken into account included operational impacts, social and environmental impacts and main transit objectives (25). In the Ottawa-Carleton rapid transit study, the factors affecting the residents of the region in their homes, the broader urban environment, other traffic impacts and staging of construction and capacity were included (36). The World Bank has categorized these factors into air pollution, noise, visual intrusion and overall speed (38).

Based on the results of this research, the available cost estimates per passenger-km and the average overall speed, as shown in Table 6.1, are mapped against each other. The mapping is shown in Figure 6.1. The results suggest that the Transitway is the most cost-effective option in providing relatively higher speed with lower cost per passenger-km than the LRT system.

For a more detailed cost-effectiveness comparison, the Transitway and the LRT systems are compared on the evaluation criteria shown in Table 6.2. The criteria are ranked according to the desirability and converted into weights. All effectiveness criteria achievement levels are transformed into relative values and then weighted by the importance of the criteria. These estimates are then mapped into a relative value scale of 0 to 1. The calculation procedure is as follows.

Table 6.1: Cost Versus Average Overall Speed

System	Transitway	LRT
Cost/pass-km (1987\$)	0.07-0.13	0.12-0.16
Average Overall Speed (km/h)	18.52-38.38	13.78-36.12

Figure 6-1 Cost effectiveness in Terms of Cost vs Average Overall Speed

Table 6.2: Cost-Effectiveness Data

Rank	Evaluation Criteria	Transitway	LRT System
1	Reduce door-to-door travel time	Very good	good
2	Comfort [*]	Very good	poor
3	Ride quality	Good	Very good
4	Area coverage	Good	Poor
5	Service frequency	Very good	good
6	Eliminate wait and transfer	Good	Poor
7	Stage construction and operation	Very good	Poor
8	Securing more ROW	Very good	Good

* indicates seat availability

1. Ranking

The effectiveness criteria are ranked from 1 to 8 according to desirability based on the results of this research. These ranks are then converted into "converted ranks" (Cr1 to Cr8) that are used in the calculation of weights.

2. Weights

The weight for each criteria is determined by the following equation:

$$W_i = Cr_i / \sum Cr \dots\dots\dots(8.1)$$

where,

W_i = Weight of the effectiveness criteria 'i'

Cr_i = Converted rank for criteria 'i'

$\sum Cr$ = Sum of all the converted ranks

3. Scale Transformation

On a scale of 0 to 1, all the effectiveness measures (W_1 to W_8) are transformed into relative values (i.e., Cr_{11} to Cr_{88}). Where Cr_{11} is the measure of effectiveness of alternative 1 in terms of criterion Cr_1 . Each effectiveness criterion can be initially assessed in its original scale or as "very good", "good" or "poor". The achievement values are transformed then into relative values. In the case of subjective assessments, relative values are assigned as well. For example, 1 is assigned to "very good", 0.75 to "good" and 0.50 to "poor".

4. Effectiveness Score

The final effectiveness score (E) for Transitway and LRT systems are computed as follows:

$$E (\text{Transitway or LRT System}) = \sum W_i x C_{ij} \dots\dots\dots(8.2)$$

where,

W_i is the weight for criteria i

C_{ij} is the j th level of effectiveness for criteria i .

The final results of effectiveness against total cost per passenger-km are shown in Figure 6.2. In Table 6.3, the results are provided in order to demonstrate the effect of changing the ranks. The results of this table are shown in Figure 6.3.

It is seen from these results that ranking of evaluation criteria plays an important role. A change in criteria ranks results in different cost-effectiveness scores for systems that are being compared. It is concluded here, once again, that the Transitway is the most cost-effective option.

Another comparative assessment, which includes buses in mixed traffic, buses in reserved lanes, Transitway and LRT systems, was based on the technique of cost-effectiveness analysis reported in Reference (19). The cost-effectiveness data used, cost versus average overall speed and the cost-effectiveness of public transit alternatives are shown in Table 6.4 and Figures 6.4 and 6.5. It is evident from Figures 6.4 and 6.5 that the Transitway is the most cost-effective option.

The criteria ranks for the above noted evaluation study, given in Table 6.4, are changed in order to study the relative changes in cost-effectiveness for various alternatives (Table 6.5). The resulting cost effectiveness information is shown in Figure 6.6. Here, once again, it is demonstrated that the Transitway is the most cost-effective option.

Therefore, it is concluded that Transitways are superior to LRT systems in terms of lower cost, average overall speed and measures of effectiveness.

Figure 6.2. Cost Effectiveness of Transitway and LRT Systems

Table 6.3: Revised Cost-Effectiveness Data

Rank	Evaluation Criteria	Transitway	LRT System
1	Reduce door-to-door travel time	Very good	Good
2	Ride quality	Good	Very good
3	Comfort [*]	Very good	Poor
4	Service frequency	Very good	Good
5	Area coverage	Good	Poor
6	Eliminate wait and transfer	Good	Poor
7	Securing more ROW	Very good	Good
8	Stage construction and operation	Very good	Poor

* seat availability

Figure 6.3: Cost-Effectiveness (Based on Revised Ranks) of Transitway and LRT Systems

Table 6.4: Effectiveness Measure and Rank

Cost/Effectiveness Data	Bus in Mixed Traffic	Buses in Reserved Lanes	Transitway	LRT Surface
Cost/pass.km (US \$ 1985)	0.035	0.035	0.065	0.125
Effectiveness Measure and Rank:				
1. Safety	Average	Average	Good	Good
2. Avg. overall speed Km/hour	11.0	16.5	22.5	20
3. Noise	Average	Average	Good	Average
4. Visual intrusion	Good	Good	Good	Average
5. Desirable land use impact	Poor	Average	Good	Good
6. Air pollution	Poor	Average	Good	V. Good

Reference: 19

Average Overall Speed (km/h)

Figure 6.4 Cost-Effectiveness (Cost vs Average Overall Speed) of Urban Transit System

Source: Reference 19

Figure 6.5: Cost-Effectiveness of Urban Transit Systems

Source: Reference 19

Table 6.5: Revised Effectiveness Measure and Rank

Rank	Evaluation criteria	Bus in mixed traffic	Bus in reserved lanes	Transitway	LRT
1	Safety	Average	Average	Good	Good
2	Av. overall speed (km/h)	11.0	16.5	22.5	20.00
3	Air pollution	Poor	Average	Good	Good
4	Visual intrusion	Good	Good	Good	Average
5	Noise	Average	Average	Good	Average
6	Desirable land use impact	Poor	Average	Good	Good

Figure 6 6: Cost -Effectiveness (Based on Revised Ranks) of the Public Transit Options

CHAPTER 7

IMPLEMENTATION ISSUES

7.1 Implementation Process

The ultimate end of every transportation planning process is the implementation of the project. The necessary inputs to the implementation process are shown in Figure 7.1. The alternative selected, which is the result of various steps of the evaluation processes, needs to be staged over the time period for implementation purposes. All funding arrangements must be identified. The construction should be staged based on the available funds and other priority measures. A pre-implementation examination of problems is desirable because it helps identify unexpected problems (70). The post-implementation phase of the plan compares actual consequences to those estimated in the analysis stage.

7.1.1 Funding Arrangements

Urban rapid transit projects are highly capital intensive. Funds are rarely available from all levels of government when most needed. In many cases where studies were done, various options were selected and eventually the necessary funds were not available from the government bodies. This resulted in abandonment or delay of the implementation.

In 1973 a rapid transit study for Ottawa-Carleton Region concluded that initial costs of \$300 million (1973\$) and \$60 million extra expenditures were necessary for

Figure 7.1: Implementation Process of Urban Transit Systems

the expansion of the transit system. This option was not implemented due to high costs that were thought to be out of reach for the regional government (39,71). Similarly in 1960, Edmonton abandoned its program of freeway network to a full rapid transit system due to fiscal constraints and non-availability of ROW (31). The LRT system was later selected and implemented. A study in 1967, which was undertaken for the city of Calgary's 32 km rapid transit system, was abandoned due to lack of funds (72).

Similarly in the United States, for Los Angeles, more than six transit studies were undertaken and none implemented — due to fiscal constraints and other reasons. The rapid transit system that is now under construction and is estimated to cost U.S \$3.17 billion (1988\$), only \$700 to \$900 million is in the bank or now committed to the project (73). In the Atlanta Region in 1971, 85 km of subway, 13 km of busway and an intensive feeder bus system was approved and scheduled for completion by 1980. Due to lack of funds and uncertain federal aid, only 22 km of rail line was eventually constructed. Other uncertainties, including costs, substantially altered the original adopted concept (20).

The evaluation of the alternatives must recognize not only the needs of the service area, but also the financial capability of the region. In planning the implementation of rapid transit system, the staging of construction has to be consistent with the availability of funds and service needs of the area. Transitway is preferable in this respect because of its low capital expenditures and the flexibility of segment by segment construction and service operation.

7.1.2 Staging

Staging of the implementation process is a key factor leading toward the successful completion of the urban rapid transit system. Urban rapid transit projects are an arduous process because of the length of time (e.g., 5 to 15 years) needed for completion. The expected expenditures need to be distributed among all the projects.

The various sources providing the funds need to be identified and their commitment assured. A serious consideration must be made regarding the benefits of the prioritization of the construction segments/projects that will be undertaken. Sufficient available funds must be assured to complete the selected segments/projects without delay. Immediate benefits of segment/project completion vs deferring or abandoning segments needs careful examination.

7.2 Staging of Transitway versus LRT System

Staging characteristics of the Transitway and LRT systems are shown in Table 7.1. Due to motor-bus technology, the Transitway option is more flexible in staging than the LRT-based system. The construction can be carried out in shorter segments and can be operated without the completion of the entire route. Segment by segment operation of services plays an important role in testing the various assumptions made during the evaluation process. Additionally, the construction can be carried out in outer sections first, which will provide the benefit of securing ROW in the early stages. This will also help guide future land use around the transit stations.

Table 7.1: Staging Characteristics of Transitway and LRT Systems

Items	Transitway	LRT
1. Possibility of construction of segments of the systems.	Short segments can be built.	The entire route (corridor) has to be built.
2. Possibility of operation segment by segment.	Segment by segment operation is possible.	LRT can not be operated in this way.
3. Development of outside segments of a corridor prior to construction of the central section.	Transitway enables such a staging flexibility.	LRT system can not be staged in this manner.
4. Securing cheap ROW in outlying areas first.	ROW can be secured in the outer areas in early stages.	Not possible with LRT system.
5. Possibility of using freeway and arterial lanes without waiting for the construction of complete system.	Transitway is flexible with this respect.	Light rail vehicle can not be operated off-the-track.

In the case of LRT system, the entire route has to be completed before any operation can take place due to its rigid technological character (7). This means that segment by segment operation is not possible. All expenditures must be made before other problems arise.

The Transitway is favourable in certain regions where line-haul buses can use the neighbourhood streets, CBD streets and available freeway or arterial lanes. For example, in the East corridor of the Ottawa-Carleton transit, a freeway lane was available. In the West corridor, a parkway lane was available for bus use only for a considerable amount of time. The parkway lane could not have been used for a LRT-based system if had been selected (64). Therefore, it is concluded that the Transitway is a more flexible option in terms of construction and operation than the LRT system.

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CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Summary of Results and Conclusions

The results of the analysis performed in earlier chapters include the following significant points:

- i) change in urban structure created the decline in rapid transit usage about two to three decades ago. In recent years, owing to positive developments in public transit, demand has increased. Despite progress in implementing rapid transit services, (mostly rail type) urban and suburban traffic congestion continues to get worse due to high travel demand;
- ii) Transitways are more effective than LRT systems in serving the travel needs and relieving congestion. Because with Transitway, the services can easily be expanded into the urban and suburban communities due to operational flexibility of motor bus technology;
- iii) Transitway can be constructed and operated in many more ways than the LRT system because LRT needs its own track for operation and can not be provided in the entire urban area due to its high capital costs. With Transitway using the exclusive facility as a part of the entire route, the existing freeway or arterial lanes are the potential sources of expanding the transit services to the entire urban area;
- v) uncertainties related to capacity analysis and forecasting error of other

transit-related items (population, employment, socio-economic characteristics of the inhabitants) means that ridership can be increased with Transitway by using higher capacity articulated buses, interlining various routes and integrating services. These operating characteristics of Transitway can not be achieved with the LRT system;

- v) a typical door-to-door urban trip consists of ten parts. Three parts for riding only and seven parts for non-ride activities such as walking, waiting and transferring. The long distance walking inability of humans and the negative attitude toward waiting and transferring are the reasons making urban transit less attractive;
- vi) with LRT systems, 90% of riders rely on feeder buses and then have to wait for the rapid transit service at the station. The remaining 10% of the riders have to wait even longer due to infrequent service. Because LRT operates in number of cars per train resulting longer headway. With Transitway these 90% of the riders escape the trouble of waiting and transferring and 10% of the riders have to wait for less time than those using LRT system. Because with Transitway, the non-ride time is less or non-existent. Also headway are shorter due to single vehicle operation, compared to LRT;
- vii) about 90% of the total riders get a "one-seat" ride with Transitway. Coupled with the express services and using the reserved lanes (exclusively for transit services) on available freeway or arterial, comparatively longer routes with relatively faster speed can be served;
- viii) because the non-captive riders dislike shorter trips (urban transit trips) in

pieces, the LRT system is unable to attract these riders. Transitway provides a one-seat ride with 15% less total trip time and 64% less non-ride time than LRT system for an exclusive route length of 10 km with access/egress of 4 km each so there is a greater chance of attracting these riders;

- ix) with Transitway the same bus can be used for door-to-door trips (avoiding waiting and transferring as well as providing more frequent service) thereby providing faster speed to the entire urban area than the LRT system;
- x) Transitways need two to three times less capital expenditure for infrastructure and vehicles than a comparable LRT-based system;
- xi) previous cost comparative studies have demonstrated bus rapid transit as a more favoured option than rail rapid transit system;
- xii) Transitway, however, gives operational benefits when the exclusive ROW facility is used as part of the entire trip. Operating more than one type of services, interlining of routes and using articulated buses, more favourable results are achieved in terms of capital as well as operating costs. For example, operating a mix of express and non-express service, the standard bus becomes 50% more cheap and the articulated bus becomes 60% more cheap compared to original costs figures;
- xiii) operationally LRT system is cheaper by 2.07 times than standard bus and 1.50 times than articulated bus per passenger basis for a route length of 6 km and 8,000 peak hour passenger volume. These ratios resulted when both LRT and Transitway services are operated in similar fashion. For the route length of 15 km, the above ratios changes to 2.19 and 1.58. But increasing the number

of peak hour passenger to 15,000, the ratios change to 2.17 and 1.53. These figures demonstrate that standard bus is more expensive operationally than LRT and articulated bus. Operationally articulated bus is more than 2 times less expensive than standard bus. Also, articulated bus gains the same advantage as LRT system. For example, the operating costs for LRT and articulated and standard bus reduced by 1.03, 1.07 and 1.05 times respectively for a route length of 15 km and peak hour passenger volume of 15,000 compared to 6 km route length and 8,000 peak hour passenger volume;

- xiv) on total cost per passenger basis, the LRT system is over two times more expensive than Transitway for route length of 6 km and peak hour passenger volume of 15,000. At route length of 15 km and peak hour passenger volume of 15,000 the LRT system is still 1.38 and 1.70 times more expensive than standard and articulated bus respectively. Here the cost superiority of the articulated bus over the standard bus is also evident;
- xv) including the operation of subway in the analyses, at 16,000 peak hour passenger volume, the standard bus is 3% more expensive than LRT system. At 19,000 peak hour passenger level both are equal. At 24,000 and 28,000 peak hour passenger volume level the standard bus is 4% and 6% cheap than LRT system respectively. LRT system is 4% more expensive than articulated bus at 16,000 peak hour passenger volumes and 18% more expensive at 28,000 peak hour passenger volume;
- xvi) at vehicle capacity with a higher load factor (design capacity), the articulated bus is more cost-efficient than both the standard bus and LRT system. With

increased load factor, the cost per passenger for articulated bus drops by 12% where for LRT system by 2% only;

- xvii) the LRT system is more sensitive to changes in various parameters (see sensitivity tests) due to its higher capital costs;
- xviii) Transitway is more cost-effective than LRT-based systems in terms of increased speed and economic efficiency; and
- xix) Transitway is more flexible in capacity staging and construction schedules. Transitway can be constructed for more than twice the length of LRT system (due to less capital costs) if funds are available. This will secure more ROW in early stages. Also Transitway can be constructed with half a length of the LRT system with equal cost and will serve the same purpose due to operational flexibility.

The level of service and cost models developed in this research proved to be a useful tool in the evaluation of rapid transit systems for medium-sized areas. The information provided in the thesis or the results of the analyses are a valuable source of information in urban rapid transit systems studies. The LOS, costing models and the cost computation procedures used in this analysis can be transferred to any location provided that local input parameters are specified.

8.2 Recommendations for Further Study

There is a definite need for further study on the subject of this thesis. Such a study could potentially supplement and refine the results of this analysis. More reliable unit operating costs for LRT systems and the actual capital and operating

unit costs for bus-subway would enhance the results provided in this thesis. In medium-sized cities (with a lack of dense corridors) where employment and suburban communities are scattered, Transitways must be seriously considered in the evaluation process involving rapid transit systems. In urban areas where freeway or arterial lanes can be used exclusively for urban transit systems, the Transitway is the most favourable option and deserves serious consideration.

Also, further research is recommended to get direct opinions on the effectiveness of either Transitway or LRT system from the builders, operators and users of the system.

Depending on the actual needs of the urban area (after service of about 20 years), Transitway can be converted to Advanced Light Rail Transit (ALRT) system or Rail Rapid Transit (RRT) system.

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APPENDIX A

CAPITAL COSTS AND RELATED DATA

Unit Costs

The reader should note that all costs are expressed in 1987\$ terms, unless otherwise stated.

Unit capital costs used in the analysis are divided into the following four categories: namely A1, A2, A3, and A4.

In the case of LRT, the unit costs A1 to A3 are obtained from Reference 13 and A4 is taken from Reference 25. The unit cost A4 is assumed to apply to the expenditure year (i.e., 1981), since the date for given cost figures in the Reference 25 is not clearly mentioned. These costs were converted to 1987 dollars. The Transitway unit costs are obtained from References 36, 64 and 74. A1 and A2 are obtained from Reference 36, while A3 is taken from Reference 64, and A4 is obtained from Reference 74.

Guideway Construction (A1): Cost/km

Transitway = \$ 5,940,000

LRT = \$ 18,038,100

ROW acquisition (A2): Cost/km

Transitway = \$ 333,670

LRT = \$ 2,362,240

Vehicle (A3): Cost/vehicle

Standard Bus = \$ 142,800

Articulated Bus = \$ 306,000

LRV (Articulated) = \$ 1,200,000

Garage and Yard & Shop (A4): Cost/vehicle

Standard Bus = \$ 53,265

Articulated Bus = \$ 79,900

LRV (Articulated) = \$ 184,260

Related Data

1. Life of Vehicles and Facilities

Economic Life

Items	Economic Life
Motor Bus	15 years
Light rail vehicle	30 years
Guideway Construction	
• Transitway (surface operation)	30 years
• LRT (surface operation)	36 years
• Tunnel	100 years
Garages	50 years
Yard & Shop	50 years
Right of way	Infinity

The life period for each of the items is taken from References 25, 38, and 39.

As LRT guideway construction is composed of various items with different life

periods (as given by Reference 38), an average of all included items is used.

It is believed that in the case of Transitway, a similar process led to the estimate of 30 years as the life of guideway construction.

2. Interest Rate

In the case of Ottawa-Carleton, a discount rate/interest rate of 10% was used for the analysis. The same is assumed for LRT costs.

APPENDIX B

OPERATING COSTS AND RELATED DATA

Unit Operating Costs

The total operating cost for Ottawa-Carleton, Edmonton, and Toronto transit systems are divided into five parts: M1, M2, M3, M4 and M5. Where,

M1 = Time-related cost = \$/bus or train-hour

M2 = Distance-related cost = \$/bus or car-km

M3 = Maintenance of route = \$/route-km (ann)

M4 = Maintenance of station = \$/station (ann)

M5 = Peak-scheduled vehicle = \$/bus or car (ann)

The allocation of operating cost on a unit basis becomes more complex due to joint costs where the same transit system consists of more than one technology (e.g., Toronto). Such a difficulty arises in the case of certain cost items that are supposed to be for the entire system.

Except Edmonton, the rest of the North American LRT transit systems do not disaggregate the operating costs into the above mentioned units.

In 1981, Biemiller & Munro (61), in an intensive study, tried to disaggregate the operating costs of the Toronto transit system. These unit costs, along with Edmonton's transit system, are shown in Table B.1.

For Ottawa-Carleton bus transit and Calgary's LRT systems, operating unit costs used in this analysis are explained below.

**Table B.1: Unit Operating Costs (1987\$) for
Selected Transit Systems**

Mode	Toronto	Edmonton
Diesel Bus		
\$/veh-hour	25.02	20.83
\$/veh-km	0.45	0.50
\$/pk-veh (ann)	16,910	33,780
Trolly Coach		
\$/veh-hour	25.02	-
\$/veh-km	0.43	-
\$/pk-veh (ann)	15,070	-
\$/route-km (ann)	31,680	-
Street Car		
\$/veh-hour	25.02	-
\$/veh-km	0.61	-
\$/pk-veh (ann)	20,440	-
\$/route-km (ann)	90,080	-
LRT		
\$/veh-hour	-	29.23
\$/veh-km	-	0.96
\$/pk-veh (ann)	-	84,560
\$/route-km (ann)	-	233,750
\$/station (ann)	-	532,950

Source: Reference 25

The reader should note that all costs are expressed in 1987 dollars, unless otherwise stated.

1. Unit Operating Costs for Buses

The Unit Operating Costs for Standard Bus are directly obtained from Reference (74). Unit costs for Articulated Bus are the same except M2. M2 for Articulated Bus is calculated by the following procedure.

Two factors affect the cost of Articulated Bus. One is labour for maintenance and the other is fuel. Articulated Bus is 1.31 times more expensive with respect to maintenance labour (75), and needs 1.44 times more fuel than Standard Bus (64). M2 for Standard Bus is divided into two parts (53).

$$\text{Maintenance Costs} = 0.15 \text{ (1976\$)} \quad (\text{B.1})$$

$$\text{Fuel, etc.} = 0.07 \text{ (1976\$)} \quad (\text{B.2})$$

Therefore, the cost for Articulated Bus is as calculated below.

$$\text{Maintenance Costs} = (\text{B.1}) \times 1.31 = 0.15 \times 1.31 = 0.20 \quad (\text{B.3})$$

$$\text{Fuel, etc.} = (\text{B.2}) \times 1.44 = 0.07 \times 1.44 = 0.10 \quad (\text{B.4})$$

$$\text{Total} = (\text{B.3} + \text{B.4}) \times \text{CPI} = 0.30 \times 2.2 = \$ 0.66 \text{ (1987\$)} \quad (\text{B.5})$$

Please note that 2.2 is obtained from the consumer price index (CPI) values for 1976 and 1987 (57).

Therefore, the unit costs for Standard and Articulated Buses used in the analysis are:

Standard Bus

$$\text{M1} = \$ 19.80$$

$$M2 = \$ 0.48$$

$$M3 = \$ 54,680 \text{ (ann)}$$

$$M4 = \$ 33,000 \text{ (ann)}$$

$$M5 = \$ 24,200 \text{ (ann)}$$

Articulated Bus

$$M1 = \$ 19.80$$

$$M2 = \$ 0.66$$

$$M3 = \$ 54,680 \text{ (ann)}$$

$$M4 = \$ 33,000 \text{ (ann)}$$

$$M5 = \$ 24,200 \text{ (ann)}$$

The articulated bus is expensive only in the case of M2.

2. Unit Operating Costs for LRT System

Reference (13) has provided the Calgary's LRT operating cost as follows (1987\$).

$$\text{Maintenance Costs} = \$4.322 \text{ million (51\%)} \quad (\text{B.6})$$

$$\text{Power Costs} = \$1.223 \text{ million (14\%)} \quad (\text{B.7})$$

$$\text{Total Operating Cost} = \$3.000 \text{ million (35\%)} \quad (\text{B.8})$$

$$\text{Total} = \$8.545 \text{ million (100\%)} \quad (\text{B.9})$$

The data that is used for the disaggregation of the total cost is 5.04 million car-kilometres, 79,000 train-hours, 69 peak scheduled vehicles, 28.6 km of system length and 30 stations. These data are obtained from References (13,35).

Time-related Costs (M1)

The Edmonton LRT system's hourly operating cost is \$ 29.23 (20,25). As both Edmonton and Calgary are in the same province, and of similar socio-economic characteristics, the same unit cost per operating hour is assumed for Calgary's LRT system.

Total time-related cost is,

$$\text{\$ } 29.23 \times 79,000 \text{ (hours)} = \text{\$ } 2,309,170 \text{ (27\%)} \quad (\text{B.10})$$

The remaining portion of the operating cost

$$= (\text{B.8}) - (\text{B.10}) = 35\% - 27\% = 8\% \quad (\text{B.11})$$

Distance-related Cost (M2)

From sources (References 32,53,60), equipment maintenance cost is 18% of the total cost. According to OC Transpo's statistics, direct vehicle maintenance cost is 65% of the equipment cost (53). This percentage might be little higher because of a larger fleet. But due to non-availability of exact figures for rail or LRT transit, the same percentage is assumed for the LRT system.

The power cost for the Toronto transit system is allocated to peak scheduled vehicle, although according to many other studies and systems, the power cost is allocated to car-kms (61). In this analysis, the power cost is allocated to car-km.

Therefore, M2 is calculated as,

$$\text{Total equipment cost} = 18\% \quad (\text{B.12})$$

$$65\% \text{ to vehicles's maintenance} = 18 \times 65\% = 12\% \quad (\text{B.13})$$

$$\text{The remaining portion} = (\text{B.12}) - (\text{B.13}) = 18\% - 12\% = 6\% \quad (\text{B.14})$$

$$\text{M2} = (\text{B.7}) + (\text{B.11}) + (\text{B.13}) = 14\% + 8\% + 12\% = 34\%$$

$$= \$2,905,300 / 5,040,000 \text{ (car-kms)} = \$0.58 / \text{car-km}$$

Route-maintenance costs (M3,M4)

Lang and Soberman allocated 15% of the cost to maintenance of way and structure (32). This cost, of course, includes the 6% portion as shown in equation (B.14). Route-km cost increases by a substantial amount in the case of subway operation compared to surface operation. The difference can be seen in Table B.1.

The administrative cost, also called semi-fixed costs are usually a fixed portion of the total costs. These costs are partially allocated to route-km and partially to schedule vehicles. The cost may range from 10% to 15%. A great portion of this cost is allocated to peak scheduled vehicles. In this analysis, 3% of the administrative costs are allocated to route-km.

Therefore, route-km cost is $= 15\% + 3\% = 18\%$

Again this cost is disaggregated into maintenance of route and maintenance of station, because the Transitway operating costs are available in the same fashion. The cost is divided between route-km and station by the same ratio as that of the Transitway.

Therefore,

$$M3 = 11\% = \$939,950 / 28.6 \text{ (route length)} = \$32,870/\text{route-km}$$

$$M4 = 7\% = \$598,150/30 \text{ (number of stations)} = \$19,940/\text{station}$$

Schedule-Peak Vehicle (M5)

The remaining cost is allocated to scheduled-peak vehicle.

$$\text{Total cost} = 100\%$$

$$M1 + M2 + M3 + M4 = 27\% + 34\% + 11\% + 7\% = 79\%$$

$$\begin{aligned}
 M5 &= 100\% - 79\% = 21\% \\
 &= \$1,794,450/69 \text{ (Peak-vehicle)} \\
 &= \$26,000/\text{scheduled-peak vehicle}
 \end{aligned}$$

The unit costs used in the analysis are as noted below.

Light rail vehicle (for the city of Calgary)

$$\begin{aligned}
 M1 &= \$ 29.23 \\
 M2 &= \$ 0.58 \\
 M3 &= \$ 32,870 \text{ (ann)} \\
 M4 &= \$ 19,940 \text{ (ann)} \\
 M5 &= \$ 26,000 \text{ (ann)}
 \end{aligned}$$

Comparing these unit operating costs with the Toronto streetcar and LRT figures, it is evident that the figures (especially M3 and M4) are quite low for the Calgary LRT system.

Operating Data

1. Operating Times

The operating times of OC Transpo are adopted in this analysis (53).

Daily Service

Weekdays operating service = 18 hours
 Saturdays operating service = 18 hours
 Sundays & Holidays operating service = 17 hours

Period of operation

Peak Period = 5 hours

Midday Period = 6.5 hours

Evening Period = 6.5 hours

2. Yearly Data

In order to annualize the operating cost data, the 1987 Calendar year is used, which consists of,

Days/year

Weekdays = 251

Saturdays = 52

Sundays & Holidays = 62

Hours/year

Peak Period

Peak hours = $251 \times 5 = 1255$

Off-Peak Period

Middays hours = $251 \times 6.5 = 1631.5 = 1632$

Evenings hours = $251 \times 6.5 = 1631.50 = 1631$

Saturdays hours = $52 \times 18 = 936$

Sundays & Holidays hours = $62 \times 17 = 1054$

= 3621

If 4 peak hour period of operation is assumed, then

Peak Period

Peak hours = 1004

Off-peak period

Midday = 1757

Others = 3747

APPENDIX C

COMPUTATIONAL STEPS FOR COSTS ESTIMATES

Capital Costs

The following formula is developed for the calculation of capital cost.

Total Capital Cost (CAC)

$$= (A1' \times L) + (A2' \times L) + (A3' \times (N + .05N)) + A4' \times (N + .05N) \quad (C.1)$$

Where,

$A1'$ to $A4'$ = The annual costs that are obtained by multiplication of $A1$ to $A4$ for Transitway or LRT system (see Appendix A) by corresponding Capital Recovery Factors (CRF).

L = The route length (km)

N = Fleet size (number of buses or cars per train) required to serve the specified number of passengers.

Furthermore, N is increased by 5% to account for the vehicles considered to be spare or being repaired.

Total Operating Costs (OPC)

Yearly operating cost is computed by the following formula.

$$\begin{aligned} \text{OPC} = & M1 \times (\text{VHRPYR}) + M3 \times (\text{VKMPYR}) + M3 \times L \\ & + M4 \times (NS + 1) + M5 \times N \end{aligned} \quad (C.2)$$

In the case of LRT, VKMPYR is converted to CKMPYR

Where,

VHRPYR = Vehicle-hour/year

VKMPYR = Vehicle-Kilometre/year

CKMPYR = Car-Kilometre/year

M1 to M5 are the unit costs as described in Appendix B.

Computational Steps

Case 1: When Operation is Restricted to Exclusive Facility

Step 1. Vehicles per hour (F)

$$\text{Buses or Trains per hour, } F = \text{Vol}/C \times U \quad (\text{C.3})$$

Where

F = number of buses or train per hour

Vol = Passenger per hour

The hour could occur during Peak, Midday or Evening periods.

C = Capacity of a Bus or LRT car

U = Number of cars/train

Where,

U = 1, For Bus and

U ≥ 1, For LRT

Step 2. Cars per hour (F1)

The trains per hour are converted into cars per hour

$$F1 = F \times U \quad (\text{C.4})$$

Step 3. Average Overall Speed (AV)

For each specified route length (i.e., exclusive facility), the average overall

speed is computed by the formula as given below.

$$AV = L \times 3600 / M \quad (C.5)$$

Where,

$$M = NS \times [(T + V/2a + V/2d)] + TR + (L \times 1000/V)$$

AV = Average overall speed (km/hr)

L = Route length (km)

NS + 1 = Total number of stations

where,

NS = Total route length/station spacing

T = Station Stop Time (sec)

a = Acceleration (m/sec/sec)

d = Deceleration (m/sec/sec)

TR = Turn around Time (sec)

V = Maximum speed (m/sec)

Step 4. Round Trip Time (RTT)

$$RTT = 2 \times L / AV \quad (C.6)$$

Where,

RTT = round trip time in hour

Step 5. Fleet Size (N)

For the Peak hour, the number of buses and train or cars are determined by the following formula

$$N = F1 \times RTT \quad (C.7)$$

Where,

N = number of buses or cars per train

Step 6. Vehicle-kilometres (V-km)

Vehicle-km are determined by the following formula

$$V\text{-km} = 2 \times L \times F \quad (C.8)$$

To convert V-km into car-km, the above formula is multiplied by $F1$ instead of F . Where F and $F1$ are defined above.

Step 7. Vehicle-Hours (V-hr)

To get Bus-hours or Train-Hours, the following equation is used.

$$V\text{-hr} = F \times RTT \quad (C.9)$$

Step 8.

The bus-hours or train-hours and bus-km or car-km are multiplied by yearly operating data to get yearly figures. The yearly operating data are given in Appendix B.

Step 9. Passenger-km/year or Pass/year

The total number of passengers/year are multiplied by the route length (trip length), so Passenger-km/year are computed. While to get the number of pass/year, the hourly passengers are multiplied by the yearly data. The following formula is used.

Pass-kmy

$$= (Vol1 \times 1255 \times TL) + (Vol2 \times 1632 \times TL) + (Vol3 \times 3621 \times TL) \quad (C.10)$$

$$Passy = (Vol1 \times 1255) + (Vol2 \times 1632) + (Vol3 \times 3621) \quad (C.11)$$

Where,

Pass-kmy = passenger-km/year

Passy = Passenger/year

Vol1 = Peak hour passenger

Vol2 = Midday hour passenger

Vol3 = Evening hour passenger

TL = Trip length (kms)

In these computations, the trip length is assumed equal to the route length because the assumed number of passengers are destined for CBD. In actual practice, the off-peak trip length is usually shorter than the peak period (53).

To calculate the pass-km/year or pass/year for a peak period of 4 hours, the corresponding volumes are multiplied by number of hours in one year for the four hour peak period as shown in Appendix B.

Step 10. Cost per Passenger-kilometre

The desired item of the cost is divided by the pass-km/year, to get the corresponding cost per pass-km.

$$\text{Total Capital Cost/Pass-km} = \text{CAC/Pass-kmy} \quad (\text{C.12})$$

$$\text{Total Operating Cost/Pass-km} = \text{OPC/Pass-kmy} \quad (\text{C.13})$$

$$\text{Total Cost/Pass-km} = (\text{CAC} + \text{OPC})/\text{Pass-kmy} \quad (\text{C.14})$$

Similarly

$$\text{Guideway Construction Cost/Pass-km} = A1' \times L/\text{Pass-kmy} \quad (\text{C.15})$$

$$\text{ROW Acquisition Cost/Pass-km} = A2' \times L/\text{Pass-kmy} \quad (\text{C.16})$$

$$\text{Vehicle Cost/Pass-km} = A3' \times (N + 0.05N) / \text{Pass-kmy} \quad (\text{C.17})$$

$$\begin{aligned} \text{Garage or Yard \& Shop Cost/Pass-km} \\ = A4' \times (N + 0.05N) / \text{Pass-kmy} \end{aligned} \quad (\text{C.18})$$

$$\text{Time-Cost/Pass-km} = M1 \times \text{VHRPYR/Pass-kmy} \quad (\text{C.19})$$

$$\text{Distance-Cost/Pass-km} = M2 \times \text{VKMPYR/Pass-kmy} \quad (\text{C.20})$$

$$\text{Route-km Cost/Pass-km} = M3 \times L/\text{Pass-kmy} \quad (\text{C.21})$$

$$\text{Station Cost/Pass-km} = M4 \times (\text{NS} + 1)/\text{Pass-kmy} \quad (\text{C.22})$$

$$\text{Schedule Vehicle Cost/Pass-km} = M5 \times N / \text{Pass-kmy} \quad (\text{C.23})$$

So if in the above cases, division is made by passy instead of pass-kmy, the cost figures per passenger will be calculated.

Case 2: Express and Non-Express Service

The Transitway offers an express service to long distance riders and the non-express service to others with little or no disturbance to its entire system. In the case of rail transit, the operation of more than one service at a time needs a third track or off-track stations with further spacing. Chicago and Philadelphia have offered the express and non-express service with the two-track facility. It was observed that the resulting headways were found to be greatly uneven. These two cities have station spacings of 5 to 8 km. Furthermore, in the case of rail transit, with a two-track facility, this type of service is possible only when the line is running well below capacity (76).

Express service is defined here as the service that takes 10 minutes less than the non-express service. All the steps shown in the operating procedure above is applicable here. The only difference is that the peak hour volume is divided into two parts. 40% of the peak hour volume is assumed to be served by express service and 60% by non-express service. The assumptions regarding the time advantage of express service and the percentage of volume served by express service have been

discussed in detail in Chapter 4. Vehicle-hour/year and vehicle-km/year are then combined for both services and various costs are calculated. The results are compared with the non-express service under similar assumptions.

The operation of express and non-express service compared with only one type service is beneficial in terms of reducing fleet size, time delays and operating costs (77). That means that riders are better off in terms of time saving and operator gets benefits in terms of decreased capital and operating costs. The express and non-express services are only considered for the Transitway system.

Case 3: Integrated Service

Integrated service consists of access/egress and rapid transit systems. The concept is shown in Figure 2.7.

To operate an integrated service, in the Transitway case, the same bus is scheduled from the start of the feeder route (i.e. access system) to the end of CBD route (i.e., egress system). In the case of Transitway integrated service, the concept of access/egress system as a separate service diminishes. In the case of the LRT system, 90% of the assumed passenger volume is served by feeder service, and 100% passenger volume is served by the LRT system, as discussed in Chapter 3. The costs for the LRT system and access/egress systems are calculated separately and are then combined to compare with the Transitway case. The cost for 10% passengers, who reach the LRT system by the walk, park-and-ride and kiss-and-ride is ignored. Also access/egress services are assumed to be equal in all respects. It is not realistic to serve 8,000 or 15,000 peak hour passengers by one feeder or connecting route. In reality, there should be more than one route for access/egress services of unequal

lengths but this will not make a big difference to the resulting cost figures, therefore, the number of routes are ignored.

Average overall speed for access/egress areas are assumed and the total round trip time is calculated by the same formulae as shown in Chapter 4. In the case of the Transitway, a weighted average overall speed (WAV) is used in the calculation. The weighted average overall speed is computed where Transitway (i.e., exclusive facility) is used as a part of the entire route as follows.

$$\text{WAV} = ((\text{FRL} \times \text{V1}) + (\text{RRL} \times \text{AV}) + (\text{CRL} \times \text{V2})) / \text{FRL} + \text{RRL} + \text{CRL}$$

Where,

WAV = Weighted average overall speed (km/h)

FRL = Feeder route length (km)

V1 = Average speed on feeder route (km/h) — 23 km/h

RRL = Rapid transit route length (km)

AV = Average speed on rapid transit route (km/h) — see step 3

CRL = CBD area route length (km)

V2 = Average speed on CBD route (km/h) — 16 km/h

The remaining procedure regarding the calculation of parameters and costs is the same one used in Case 1. It is to be noted that in the calculation of cost for feeder and connecting services, the equations (C.1) and (C.2) are used but exclude the capital costs related to roadway and station construction, and operating and maintenance costs for roadway and station. This is because these facilities are used for other travel purposes (e.g., local and cross town transit services) and non-transit services (e.g., automobiles and trucks).

Case 4: Subway in CBD Area

Bus transit tunnels in the CBD area as a part of the rapid transit route do not yet exist in North American cities. The only bus-subway under construction, is in Seattle, Washington, D.C. The Seattle tunnel is 2.1 km long with 5 stations and is supposed to cost \$430 million U.S (67,78). The dollars are assumed to be 1989 dollars. Conversion is made for the cost figure into Canadian dollars and cost is then shown in 1987 dollar value (58). The resulting cost is 224.17 millions/km. The Edmonton LRT system subway portion is 1.6 kms long with two stations and costs 53.41 million/km (1987\$).

From these costs figures, it is concluded that the Seattle bus subway is expensive because it has more station per km length than the LRT system of Edmonton and includes some sort of ventilation. The ventilation cost is 5% to 9% more for diesel buses. This cost figure for bus subway is 41% more than that of estimated value for a deep bore tunnel with two stations per kilometre in soft rock (9). This means that the subway cost can be reduced by reducing the number of stations, the type of tunnel and the use of non-diesel buses. The tunnel bore section itself is a small part of the overall subway costs that consists of stations, track/roadway, ventilation and other miscellaneous items.

LRT System (Edmonton)

1. Capital Costs

Guideway Construction Costs (A1) Reference (25,35)

Section — 1.6 km = \$ 45.70 million (1978\$) = \$ 85.46 million (1987 \$)

$$= \$ 53.41 \text{ million/km (1987 \$)}$$

$$\text{Section — 5.6 km} = \$ 2.2 \text{ million/km (1987\$)}$$

$$= \$ 4.12 \text{ million/km (1987\$)}$$

$$\text{Section — 1.7 km} = 10.50 \text{ million (1981\$)} = \$ 14.49 \text{ million (1981\$)}$$

$$= \$ 8.52 \text{ million/km (1987\$)}$$

$$\text{Section — 1.6 km} = \$ 110 \text{ million (1983\$)} = \$129.80 \text{ (1987\$)}$$

$$= \$ 81.13 \text{ million/km (1987\$)}$$

Therefore,

$$\text{Subway portion is} = 53.41 \text{ million/km (1987\$)}$$

$$\text{Surface portion (weighted cost)} = 18.80 \text{ million/km (1987\$)}$$

Where

$$\begin{aligned} * &= (5.6 \text{ km} \times \$4.12 \text{ million/km}) + (1.7 \text{ km} \times \$8.52 \text{ million/km}) \\ &\quad + (1.6 \text{ km} \times \$81.13 \text{ million/km}) / (5.6 \text{ km} + 1.7 \text{ km} + 1.6 \text{ km}) \\ &= \$ 18.80 \text{ million/km} \end{aligned}$$

$$\text{Vehicle cost/unit (A3)} = \$ 1.2 \text{ million (1987\$)} - (\text{Reference 13})$$

$$\text{Yard \& shop cost/unit vehicle (A4)} = \$ 478,800 \text{ (1987\$)} - (\text{Reference 25})$$

A2 (i.e., ROW acquisition costs) is included in A1 because separate costs are not available.

2. Operating Costs

Operating costs are the same as shown in Table B.1. The maintenance of route and maintenance and operation of station for subway are quite high compared to LRT surface operation.

Ottawa-Carleton Bus Subway

Since the comparison can be made only when both routes are of equal lengths, the bus subway is assumed to be 1.6 km and the remaining route 8.9 km.

1. Capital Cost

Guideway Construction Cost (A1)

Subway portion — (1.6 km) = 224.17 million/km (1987\$) — (Reference 67,78)

Surface portion — (8.9 km) = \$ 6.28 million/km — (Reference 36)

The cost per unit vehicle (A3) and the bus garage costs (A4) are the same as shown in Appendix A. The ROW acquisition cost is included in A1 costs.

2. Operating Cost

Subway operating costs are higher than surface operation costs. The Toronto transit system's cost figures show that the subway route maintenance costs are 25% higher than the streetcar costs and station maintenance costs are 200% higher than the route maintenance costs of subway (61).

It is assumed that the bus-subway might experience the same station maintenance costs but the route maintenance costs will be less than the rail subway system costs because of the roadway as compared to rail subway system.

In this analysis, the Transitway's existing operating cost (see Appendix B) figure for route maintenance (M3) is increased by 20% (i.e., 5% less than the Toronto) and the station maintenance cost (M4) is 200% more than for route maintenance costs. The comparison for operating costs is made with the Edmonton's LRT system.

Annual Equivalent Costs

The subway portion of the rapid transit lasts longer than the surface portion. The subway portion consists of a tunnel bore, stations, roadway/track, ventilation and numerous other minor items varying in life period. The bore section itself does not cost much compared to the rest of the items. Due to non-availability of the exact breakdown figures on cost and life basis, it is assumed that 30% of subway costs lasts for 100 years and 70% for 36 and 30 years for LRT and Transitway Guideway construction. These life periods, along with the cost and life period for vehicles, garage and yard and shop costs are given in Appendix A.

LRT System

$$\text{Annual Equivalent Cost (AEC)} = \text{Capital cost} \times \text{CRF}$$

Where,

$$\text{CRF} = \text{Capital Recovery Factor}$$

$$\text{Total costs (1.6 km length)} = \$85.456 \text{ million}$$

$$\text{Cost/km} = \$53.41 \text{ million/km} \text{ — (see A1 above)}$$

$$30\% \text{ cost (life} = 100 \text{ years)} = \$1.602 \text{ million/km}$$

$$70\% \text{ cost (life} = 36 \text{ years)} = \$3.864 \text{ million/km}$$

$$8.9 \text{ km surface portion (life} = 36 \text{ years)} = \$ 1.943 \text{ million/km}$$

Therefore,

$$\text{Weighted annual equivalent cost/km (A1')} \text{ is,}$$

$$= \$1.602 \text{ million/km} \times 1.6 \text{ km} + 3.864 \text{ million/km} \times 1.6 \text{ km}$$

$$+ 1.943 \text{ million/km} \times 8.9 \text{ kms/1.6 km} + 1.6 \text{ km} + 8.9 \text{ km}$$

$$= \$ 2.48 \text{ million/km}$$

$$\text{Vehicle cost/unit (A3')} = \$127,295/\text{vehicle}$$

Yard and shop cost (A4') = \$18,585/vehicle

Transitway

Total subway cost/km = \$224.17 million

30% cost (life = 100 years) = \$ 6.73 million/km

70% cost (life = 30 years) = \$ 16.65 million/km

8.9 km surface portion (life = 30 years) = \$666,180/km

Therefore,

Weighted annual equivalent cost/km is = \$ 6.73 million x 1.6 km
 + 16.65 million x 1.6 km + \$666180 x 8.9 km/ 1.6 km + 1.6 km
 + 8.9 km = \$4.128 million/km

Vehicle cost (A3')

= \$ 18775/unit (Standard bus)

= \$ 40230/unit (Articulated bus)

Garage cost (A4'):

= \$ 5370/unit (Standard bus)

= \$ 8060/unit (Articulated bus)

Therefore, for the subway cost computation, the following values are used:

	Ottawa-Carleton Transitway	Edmonton LRT
Capital Costs		
A1'	\$4.128 million	\$2.48 million
A2'	-	-
A3'	\$18,775	\$127,290
	\$40,230	

A4'	\$18,775 *	\$18,585
	\$40,230 #	

Operating costs

M1	\$19.80	\$29.30
M2	\$0.48	\$0.96
M3	\$65,620 (ann)	\$233,750 (ann)
M4	\$131,240 (ann)	\$532,950 (ann)
M5	\$5,370 * (ann)	\$85,560 (ann)
	\$8,060 # (ann)	

* Standard Bus

Articulated Bus

END

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FIN