RELIABILITY AND DELAY IN LRT OPERATION IN CALGARY

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ABSTRACT

Due to many issues in LRT operations, the target headway is not achieved regularly. Trains are often delayed, and the level of service is not considered satisfactory by many passengers. Calgary Transit's Light Rail Transit (LRT) system consists of around 44km of double-line rail track, which operates from Crowfoot to Somerset - Bridlewood and from the City centre to McKnight - Westwinds. From 10th St. SW to 3rd St. SE, both lines operate in a free fare zone. Many at-grade railway crossings are present in the free fare zone; and, all the intersections are signalized, allocating the higher right of way to the LRT system. To improve the reliability of the LRT system in Calgary operational problems are analyzed including delay distribution at end and time points, actual to planned headway ratios at selected stations, and inter-station delays, and recommendations made regarding improvements to the schedule and operational procedures.

INTRODUCTION

Train transit systems play a vital role in urban passenger transport, since they carry a significant percentage of passengers per unit time compared to other modes. Generally, rail is preferred over bus transportation because of comfort, high speed, safety and reliability. Maintaining scheduled departure times of the trains is a tedious task, due to variation in passenger boarding and alighting times, at-grade railway crossings, adverse weather conditions, and poor planning and operations. The situation can become critical when trains operate at higher frequencies and knock-on delay (the impact of a proceeding train on following trains) affects operations.

The 'time reliability' for passengers is defined as the probability that the planned arrival time will be achieved for each train (Higgins & Kozan, 1995). Since train delays increase the operating cost of the system and travel-time cost to passengers, it is necessary to analyze the reliability of

the rail system and develop solution mechanisms to minimize delay of trains. According to Vromans (2005), some of the measures of reliability of trains are punctuality of trains at starting, end and mid points, transfer punctuality, number of cancelled trains, average train delay and average passenger delay.

Both lateness and earliness of the arrival time is a cost for the passenger, since late arrivals cause knock-on delays, while early arrivals cause idling of trains at railway stations. The expected cost of lateness is a function of the cost of the scheduled trip time and, similarly, of earliness (Carey, 1998; Wirasinghe, 1993, 1995a, 1995b). According to Carey (1998), the time shift due to the behavioural response of the driver or operator can be calculated considering the fraction of slack time, given by:

$$(T - T_1^m)$$

where T is the allocated time for the train and T_1^m is the minimum actual schedule time.

Wirasinghe and Liu (Wirasinghe, 1993; Wirasinghe and Liu, 1995a, 1995b) studied the reliability of transit and how it can be optimized relative to travel time, delay and penalty costs through the proper use of time points and slack time. The risk of a train delay is the product of the probability of a train being delayed by the amount of that delay. For example, the total amount of risk of delay between origin and destination represents the likely delay for the train at its destination averaged over a long period. The risk of delay for any train is the difference between the probable delay incurred by the train and the expected recoverability from that delay, which is a function of train type, distribution of length and sources of delays for both the train and track (Ferreira & Higgins, 1996).

The risk of en-route delay is a function of the probability of a slowdown delay on a track segment, the amount of speed reduction, the length of time of the speed restriction, and the probability of occurrence of that length of time. The stoppage delay of trains due to the other trains on the track segment can also be determined by the same procedure (Higgins et al., 1995). In real-time conflict resolutions, the two situations of fixed or variable speed can be considered in analyzing the buffer time of trains, taking into account the time that trains enter a certain section, the clearing and switching time of trains, the approaching time of trains and the running time (Ariano et al., 2007)

Railway junction conflicts occur when two trains from different directions arrive at the junction at the same time; therefore, the scheduling should be adjusted according to the first in first out principle. Highly effective resolution methods are not necessary when fewer trains are involved in the system (Ho & Yeung, 2001).

CALGARY TRANSIT STUDY AREA

The Calgary Transit Light Rail Transit (LRT) system operates on 44 km, based on three lines – Northwest, Northeast and Southwest. The LRT system is 87% surface, 5% grade separated and

8% underground (Hubbell & Colquhoun, 2006). All three lines connect in the CBD, which is a free fare zone. Five rail stations in each direction are shared by all three lines and the buses operating on 7th Avenue SW also share part of the rail track (Figure 1). Many short distance trips are made within the CBD section, due to the free fare service between 10th St. SW to 3rd St. SE stations.

Figure 1: Map of the Calgary Transit Network (Source: Calgary Transit)

In this study, the Northeast (NE) railway line, which consists of eight LRT stations outside the CBD, from the Bridgeland station to the McKnight - Westwinds station and five rail stations within the CBD, were studied. The total length of the NE line is 14.6 km from the 10th St. SW to the McKnight - Westwinds station. According to Calgary Transit, the NE line carries a ridership of around 30,000 passengers per weekday. Around 150 train trips are scheduled to serve the demand on weekdays and 100 per day during weekends. In operations planning, a fixed dwell time is used for all the railway stations, and the departure time of each train at each station is monitored by the Calgary Transit Control Centre.

METHODOLOGY

Punctuality of Trains at Stations

The punctuality of trains is the probability of the departure of trains with a delay of less than 'x' minutes, where *x* = 1, 2, …. 5 minutes (Vromans, 2005). The delay can be caused by variations in demand, operational difficulties, and mechanical faults of trains or signal systems. When trains operate with shorter headways, especially in peak times, the delay of one train impacts the departure time of trains behind it. If the scheduled departure time of train i from station k is DT_{sik} and the actual departure time is DT_{aik}, the delay of the train *i* at station k (D_{ik}) is given by:

$D_{ik} = DT_{aik} - Dt_{sik}$ for all trains i leaving station k

Two sets of trains, i = {1, 2, 3 …….m} in the inbound direction and i = { 1, 2, 3 …… n}, for the outbound direction were considered in the study. The number of scheduled trains varied for weekdays, Saturdays and Sundays. The probability of delay from the scheduled departure time was calculated by:

$P\{D_{ik} \leq Q\}$ for Q = -2, -1, 0, 1, 2, 3, 4, 5, ……

where Q is the delay in the scheduled departure time in minutes, and $Q < 0$ indicates an early departure of the train.

In this study, we:

- Identify the percentage of trains leaving earlier than the scheduled time,
- Compare the punctuality of trains at defined 'time points' of the NE line,
- Identify sections causing significant delays in travel time,
- Calculate the mean and standard deviation of travel time for trains, and
- Identify the causes of delays in peak and off-peak times of the day.

The mean travel time, MTT_{ij}, between station i and j was analyzed as:

$$MTT_{ij} = \frac{1}{N} \sum_{i=1}^{n} TT_{ij} \text{ for all stations and both directions}$$

Penalty of Cancelling a Train

When a passenger arrives at station *k* and waits for the next train i, his/her maximum waiting time at the station is equal to the headway of the train. Nevertheless, the waiting time of the passengers increases in situations where a train is (or several consecutive trains are) cancelled. Therefore, the maximum waiting time of the passengers or the revised headway between two trains straddling one or more cancelled trains is given by:

$$\mathbf{h}_{aci} = \mathbf{h}_{sci} + \sum_{i=1}^{n} h'_{sci}$$

where h_{aci} – actual headway of train *i*
h_{sci} – scheduled headway of train *i*
h'_{sci} – headways of all consecutive cancelled trains
n – number of consecutive cancelled trains

The insertion of new trains that are not included in the original schedule improves the waiting time of the passengers. For such trains, the schedule time was considered to be the same as the actual time.

Three scenarios were analyzed to measure the reliability of the LRT system in each direction: if trains depart on time, the actual headway (h_{aci}) = h_{sci}; if the trains depart before the scheduled time, $h_{aci} < h_{sci}$; and, if trains are delayed, $h_{aci} > h_{sci}$.

The headway ratio, HWR, is defined as:

$$HWR = \frac{\mathbf{h}_{aci}}{\mathbf{h}_{sci}} \qquad \forall \text{ trains } i=1, 2, 3, \ldots\ldots\ldots$$

where h_{aci} – actual headway of train *i*
h_{sci} – scheduled headway of train *i*

The measurement of the HWR was used to identify the gap between trains in different sections of the NE line. Variation of the HWR indicates the most critical areas of the NE line with a higher percentage of conflicts and the sections where drivers tend to speed up the train to reach the destination terminal on time. A higher HWR signifies an increase in the gap between the trains. When the HWR is less than one, it shows that the trains have come closer due to early departures than scheduled.

ANALYSIS

LRT Passenger Demand Data

According to the passenger count survey carried out by Calgary Transit in 2007, around 30,000 passengers use the NE line to access the CBD for different trip purposes. The Marlborough and Whitehorn stations are the busiest in the NE line, handling more than 18,000 boardings and alightings per day (Figure 2).

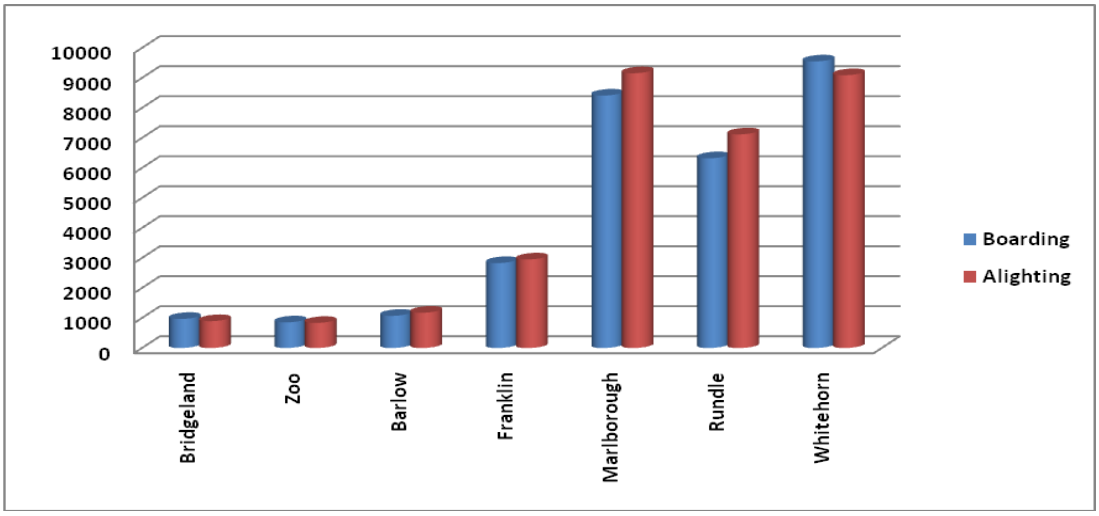

Figure 2: Total Boarding and Alighting Variation in LRT Stations on the NE Line (Source: Calgary Transit)

The Bridgeland, Barlow and Zoo stations are not heavily used, and the passenger demand is around 2,000 per day. The end terminal, the McKnight - Westwinds station, was not yet operational during the time of the passenger survey.

Delay Distribution of Trains

The delay distribution of trains was determined for the two end terminals, the 10th St. SW and McKnight - Westwinds stations, and the two time points, the Marlborough and Bridgeland stations, to analyze the starting delay of trains and delay at the time points, respectively, on the NE line (Figures 3 – 6).

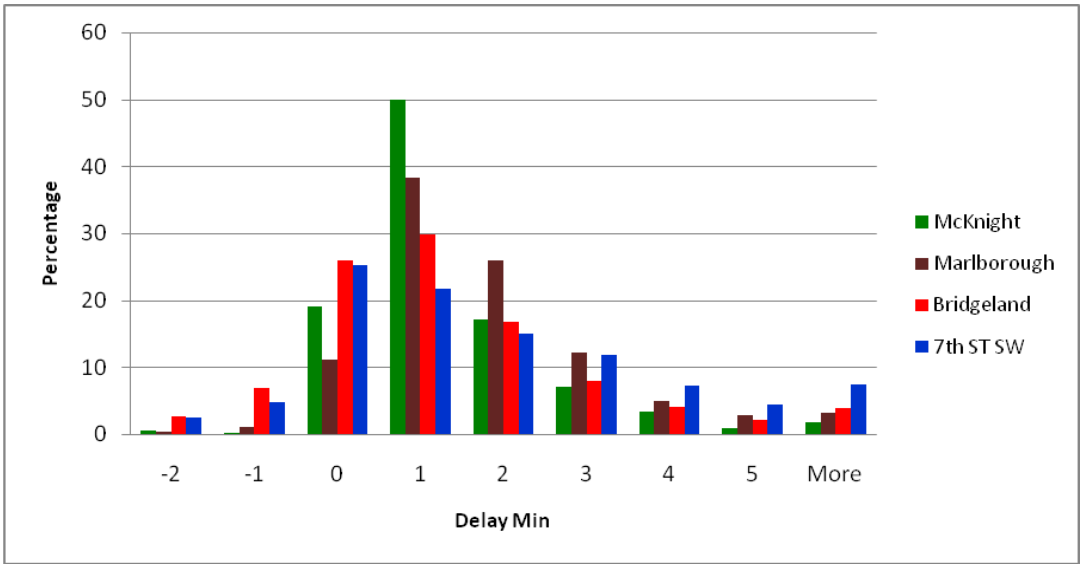

Figure 3: Delay Distribution of Inbound Trains – Weekdays

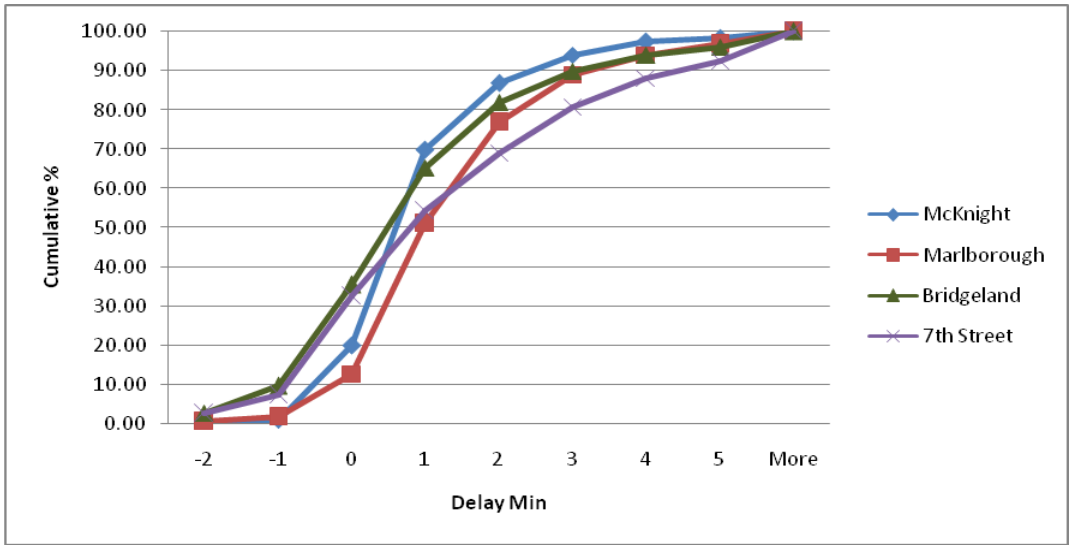

Figure 4: Cumulative Delay Distribution of Inbound Trains – Weekdays

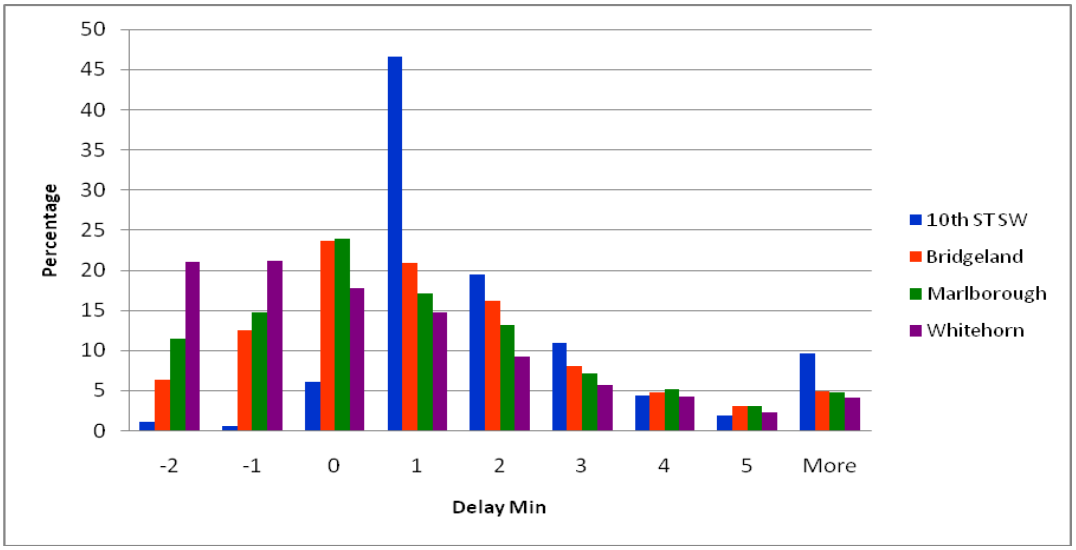

Figure 5: Delay Distribution of Outbound Trains – Weekdays

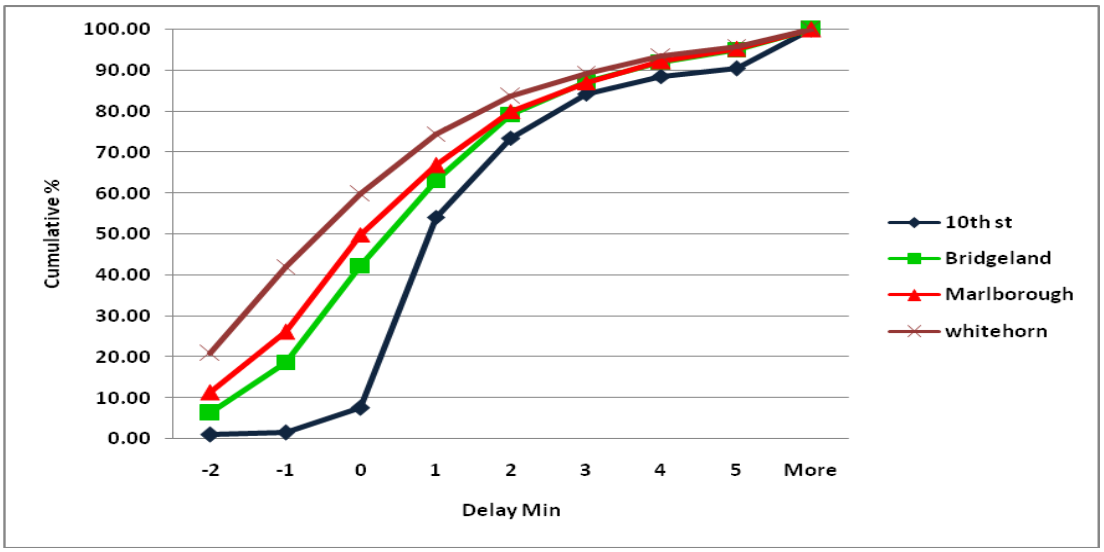

Figure 6: Cumulative Delay Distribution of Outbound Trains – Weekdays

According to Figure 3, in the inbound direction, only 20% of the trains depart on time and around 50% of the trains depart one minute late. When the trains depart the Marlborough station, around 40% and 25% of trains are delayed by one minute and two minutes, respectively. However, the drivers tend to recover from the delay by the time the trains reach the Bridgeland station. The delay of trains increases within the CBD section: around 20% of the trains are delayed by three or more minutes when the trains depart the 7th St. SW station. The

cumulative delay distribution (Figure 4) shows the increase in delay across the CBD, and around 30% of the trains are delayed by more than two minutes.

Figure 6 depicts that, in the outbound direction, only 5% of the trains depart on time, around 45% of the trains depart one minute late, and around 10% of the trains are delayed more than five minutes late. However, at the Bridgeland station, around 45% of the trains depart either on time or are delayed by one minute. Early departures from the Bridgeland station indicate poor adherence of trains to the schedule within the CBD section. The percentage of early departures goes up to 40% when trains leave the Whitehorn station.

Headway Ratios at Individual Stations

According to the HWRs for the two end terminals and two time points, around 42% of the trains depart from the McKnight - Westwinds station with the scheduled gap between adjacent trains, although each train may be delayed by an equal amount. Around 40% of the trains depart with a HWR of 1.25, and 10% have a HWR of more than 1.25. When the trains reach the Marlborough and Bridgeland stations, the operating pattern changes. Around 12% of the trains leave before the scheduled headway, and approximately 35% depart with a HWR of 1.25. However, when trains cross the CBD section, around 20% depart with a HWR of 0.75 or below at the 7th St. SW station (Figure 7).

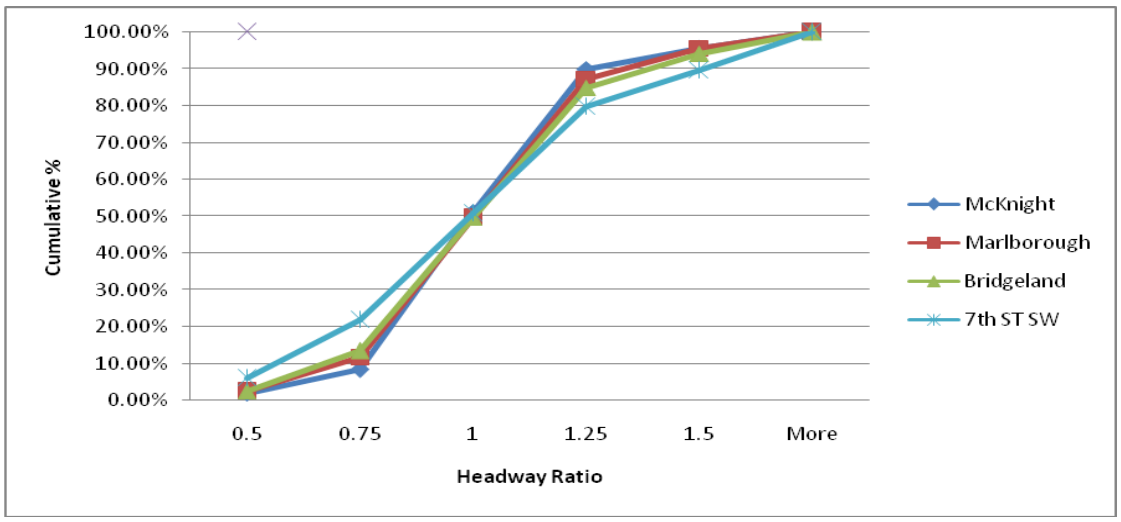

Figure 7: Cumulative Headway Ratio Distribution – Inbound Direction

Considering the outbound direction, only 40% of the trains depart within the scheduled headway. Eleven percent have a HWR of less than 1.0, and 38% have a HWR of 1.25. Once the CBD section is crossed, the percentage of trains with a HWR of 0.75 increases by 10% and with a HWR of 1.25 decreases by 10% (Figure 8). Therefore, train operation can be identified in two different patterns: ‘within the CBD section’ and ‘outside the CBD section’.

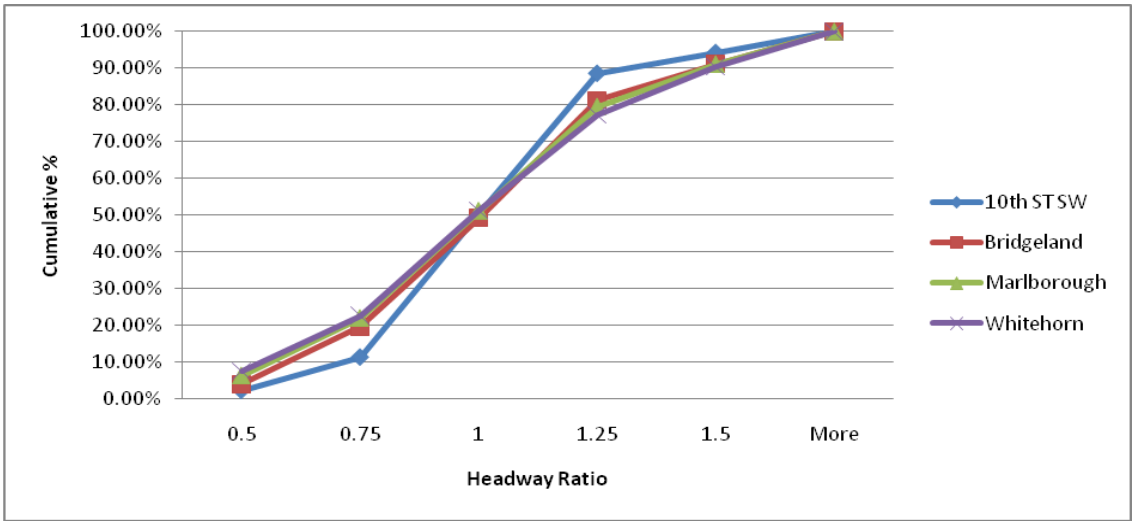

Figure 8: Cumulative Headway Ratio Distribution – Outbound Direction

The headway ratio of trains at each station along the NE line were compared for weekdays. In the inbound direction, the percentage of trains with a HWR of 1.00 decreases from the the McKnight - Westwinds station to the Marlborough station and from the Bridgeland station to the 7th St. SW station. The HWR of 1.25 is reduced by 3% outside the CBD and by 7% within the CBD. Nevertheless, the HWR of 0.75 increases by 5% outside the CBD and increases by another 5% within the CBD (Figure 9).

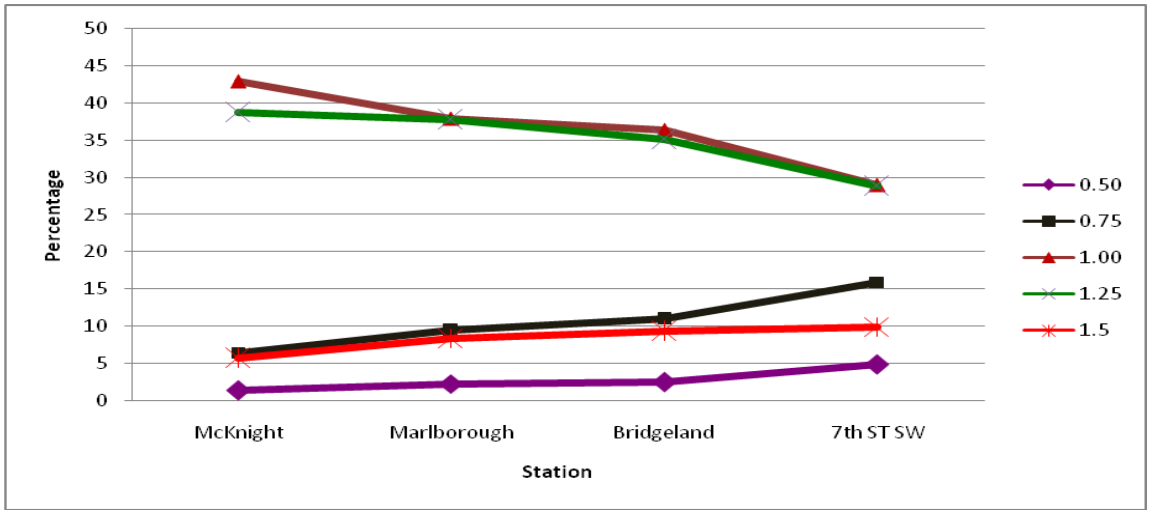

Figure 9: Headway Ratio for Stations in the Inbound Direction – Weekdays

In the outbound direction, the percentage of trains with a HWR of 1.00 decreases by 9% within the CBD and remains constant towards the end terminal, the McKnight - Westwinds station. There is a similar pattern for trains with a HWR of 0.75 with an increase of 6.5% within the CBD.

The percentage of trains with a HWR of 1.25 drops by 13% between the two end terminals of the NE line, and trains with a HWR of 1.5 and 0.5 increase by 7.5% and 6%, respectively, throughout the NE line (Figure 10).

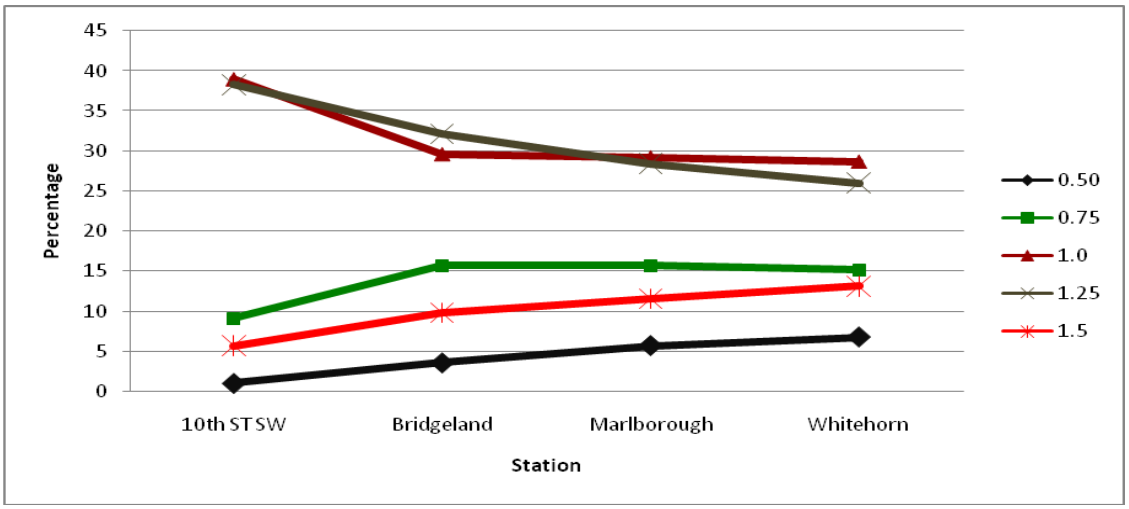

Figure 10: Headway Ratio for Trains in the Outbound Direction – Weekdays

In addition, the headway ratios for the two time points, the Bridgeland and Marlborough stations, were analyzed for peak and off-peak times separately. In the inbound direction, the percentage of trains with a HWR of 1.00 decreases by 8%, with a HWR of 0.75 increases by 6%, and with a HWR of 0.5 increases by 2% within the CBD section. Since three train lines share the CBD section and there are 16 at-grade intersections, a lower HWR can cause many train-train, train-car and train-pedestrian conflicts. The percentage of trains with HWRs of 1.00 and 1.25 remains the same outside the CBD.

Inter-Station Delays

The travel times between stations were planned by Calgary Transit based on the average operating speed of trains. The actual average speeds of the LRT trains on the NE line are 39km/h and 13km/h outside and within the CBD section, respectively (Andreas, 1983). The scheduled travel time consists of the travel time between stations and the dwell time at each station, which is currently considered as a constant. In the inbound direction, the most critical section is the link between the Bridgeland and 3rd St. SE stations, with none of the trains travelling within the scheduled time (Table 1). More than 30% of the trains are delayed by two or more minutes in afternoon peak and off-peak hours, and 50% in the morning peak hours. However, when trains arrive at the 10th St. SW station, 60% of those arrive earlier during the morning peak time.

Table 1: Percentages of the Actual Travel Time Variations from the Scheduled Travel Time (Inbound Direction)

From	Time (Hrs)	Delay (Minutes)						
		-2	-1	0	1	2	3	more
McKnight to Whitehorn	6.00 - 9.00	1	0	13	82	3	1	0
	9.00 - 15.00	1	0	25	72	0	0	1
	15.00 - 18.00	1	1	21	75	1	0	1
Whitehorn to Rundle	6.00 - 9.00	0	0	95	4	0	0	0
	9.00 - 15.00	0	0	96	3	1	0	0
	15.00 - 18.00	0	0	95	4	1	0	0
Rundle to Marlborough	6.00 - 9.00	0	0	97	3	0	0	0
	9.00 - 15.00	0	0	0	99	1	0	0
	15.00 - 18.00	0	0	0	97	2	0	1
Marlborough to Franklin	6.00 - 9.00	0	0	98	1	0	0	0
	9.00 - 15.00	0	1	99	0	0	0	0
	15.00 - 18.00	0	0	100	0	0	0	0
Franklin to Barlow	6.00 - 9.00	0	0	97	3	0	0	0
	9.00 - 15.00	0	0	99	1	0	0	0
	15.00 - 18.00	0	0	99	0	0	0	0
Barlow to Bridgeland	6.00 - 9.00	0	0	72	23	3	1	1
	9.00 - 15.00	0	0	0	96	4	0	0
	15.00 - 18.00	0	0	0	94	5	1	0
Bridgeland to 3rd St. SE	6.00 - 9.00	0	0	0	50	35	10	5
	9.00 - 15.00	0	0	0	67	30	2	1
	15.00 - 18.00	0	0	0	63	27	7	3
3rd St. SE to 10th St. SW	6.00 - 9.00	1	60	15	18	4	1	2
	9.00 - 15.00	0	4	65	18	5	3	6
	15.00 - 18.00	0	4	58	10	10	7	11

In the outbound direction, more than 95% of trains need one more minute than scheduled to travel from the Franklin to Marlborough stations. Except for the CBD section, the travel time of the trains are within a few seconds of the scheduled travel time. In the CBD section, only 21% and 24% of the trains run according to the scheduled travel time in the morning and afternoon peaks, respectively. Seventy-two percent of the trains arrive less than one minute from the scheduled travel time during the morning peak, and 55% arrive less than one minute from the scheduled travel time during the afternoon peaks. On the other hand, 41% of the trains are delayed more than one minute during the off-peak time between 09.00 to 15.00 hours (Table 2).

Trains are delayed in this direction at four stations, namely the Whitehorn, Marlborough, Bridgeland and 3rd St. SE stations. When the trains arrive at the 3rd St. SE station, two-minute delays increase, due to track interlocking at the entry point to the CBD.

Table 2: Percentages of the Actual Travel Time Variations from the Scheduled Travel Time (Outbound Direction)

From	Time (Hrs)	Delay (Minutes)						
		-2	-1	0	1	2	3	more
10th St. SW to City Hall	6.00 - 9.00	43	29	21	6	1	0	0
	9.00 - 15.00	1	24	33	25	10	5	1
	15.00 - 18.00	26	29	24	12	5	2	2
City Hall to Bridgeland	6.00 - 9.00	0	0	62	36	1	1	0
	9.00 - 15.00	0	0	64	34	1	0	0
	15.00 - 18.00	0	0	65	32	2	0	0
Bridgeland to Barlow	6.00 - 9.00	0	0	97	2	0	0	0
	9.00 - 15.00	0	0	96	3	1	0	0
	15.00 - 18.00	0	0	93	6	0	0	0
Barlow to Franklin	6.00 - 9.00	0	0	99	1	0	0	0
	9.00 - 15.00	0	0	97	2	0	0	1
	15.00 - 18.00	0	0	87	13	0	0	0
Franklin to Marlborough	6.00 - 9.00	0	0	1	98	1	0	0
	9.00 - 15.00	0	0	2	97	1	0	0
	15.00 - 18.00	0	0	0	96	3	0	1
Marlborough to Rundle	6.00 - 9.00	0	0	99	1	0	0	0
	9.00 - 15.00	0	0	99	1	0	0	0
	15.00 - 18.00	0	0	97	2	0	0	0
Rundle to Whitehorn	6.00 - 9.00	0	0	93	4	0	2	1
	9.00 - 15.00	0	0	90	7	1	1	2
	15.00 - 18.00	0	0	89	9	2	0	1

Since the Marlborough station is a high-demand station, the expected dwell time is higher than the planned constant amount. Since the scheduled inter-station travel times are higher than the actual travel times in many sections, the delays due to higher dwell times in stations are covered by the extra travel times. The actual travel times of trains are less than the scheduled times by a few seconds for most of the time periods in the NE line (Table 3.2).

Table3 indicates that the standard deviation of the travel time exceeds one minute between the McKnight - Westwinds and Whitehorn stations during off-peak hours, the Bridgeland and 3rd St. SE stations during the morning peak, and the CBD section in both the morning and afternoon peaks. However, the average travel times of trains are less than the scheduled travel times between the links of the Whitehorn and Rundle stations, the Marlborough and Franklin stations and the Franklin and Barlow stations.

Table 3: Statistical Observation of Travel times (Inbound Direction)

Section	Time	Average Travel Time		Standard Deviation	Minimum		Maximum	
		Schedule	Actual	Actual	Schedule	Actual	Schedule	Actual
McKnight to Whitehorn	6.00 - 9.00	03:04	03:20	00:33	00:00	00:00	09:00	09:30
	9.00 - 15.00	03:02	03:17	01:11	03:00	02:48	12:00	18:59
	15.00 - 18.00	03:05	03:16	00:38	03:00	02:50	08:00	12:52
Whitehorn to Rundle	6.00 - 9.00	02:00	01:43	00:14	02:00	00:59	02:00	04:02
	9.00 - 15.00	02:03	01:44	00:17	02:00	01:28	12:00	04:51
	15.00 - 18.00	02:00	01:44	00:16	02:00	01:25	02:00	04:36
Rundle to Marlborough	6.00 - 9.00	03:00	02:38	00:19	03:00	00:58	04:00	07:07
	9.00 - 15.00	02:00	02:34	00:09	02:00	02:16	02:00	03:17
	15.00 - 18.00	02:00	02:38	00:38	02:00	01:43	02:00	10:47
Marlborough to Franklin	6.00 - 9.00	03:00	02:22	00:22	03:00	02:06	03:00	06:57
	9.00 - 15.00	03:00	02:15	00:26	03:00	01:58	03:00	10:55
	15.00 - 18.00	03:00	02:16	00:08	03:00	01:56	03:00	02:51
Franklin to Barlow	6.00 - 9.00	02:00	01:42	00:09	02:00	01:00	02:00	02:51
	9.00 - 15.00	02:01	01:37	00:06	02:00	01:23	12:00	02:25
	15.00 - 18.00	02:00	01:38	00:07	02:00	00:55	02:00	02:39
Barlow to Bridgeland	6.00 - 9.00	04:00	03:57	00:41	04:00	03:09	04:00	10:23
	9.00 - 15.00	03:00	03:36	00:14	03:00	03:15	03:00	05:38
	15.00 - 18.00	03:00	03:38	00:15	03:00	03:15	03:00	05:26
Bridgeland to 3rd St. SE	6.00 - 9.00	02:00	03:18	01:10	02:00	01:41	02:00	13:20
	9.00 - 15.00	02:00	02:51	00:33	02:00	02:03	02:00	07:00
	15.00 - 18.00	02:00	03:01	00:49	02:00	02:04	02:00	07:33
3rd St. SE to 10th St. SW	6.00 - 9.00	07:58	07:17	01:12	07:00	05:38	08:00	18:43
	9.00 - 15.00	07:02	06:55	00:52	07:00	05:50	08:00	12:33
	15.00 - 18.00	07:58	08:08	01:10	07:00	05:47	08:00	15:05

According to Table 4, the standard deviation (SD) of travel time varies from 1:23 to 2:22 minutes in the CBD section, while it varies around 30 seconds from the City Hall to Bridgeland stations. For the last section, the Rundle to Whitehorn stations, the SD varies from 33 seconds in the morning peak to 47 seconds in off-peak times and 38 seconds in the afternoon peak. Since the Whitehorn station has the highest boarding and alighting, a higher SD of travel times of trains is expected, due to dwell time variations.

Table 4: Statistical Observation of Travel Times (Outbound Direction)

Section	Time	Average Travel Time		Standard Deviation	Minimum		Maximum	
		Schedule	Actual	Actual	Schedule	Actual	Schedule	Actual
10th St. SW to City Hall	6.00 - 9.00	09:58	08:13	01:23	09:00	01:09	10:00	14:55
	9.00 - 15.00	08:04	07:57	01:25	08:00	01:11	10:07	19:11
	15.00 - 18.00	09:56	08:58	02:22	09:00	01:55	10:00	33:58
City Hall to Bridgeland	6.00 - 9.00	03:00	03:01	00:26	03:00	02:24	03:00	06:10
	9.00 - 15.00	03:00	02:59	00:22	03:00	02:27	03:00	07:07
	15.00 - 18.00	03:00	03:00	00:27	03:00	02:22	03:00	07:42
Bridgeland to Barlow	6.00 - 9.00	04:00	03:32	00:11	04:00	03:16	04:00	05:19
	9.00 - 15.00	04:00	03:35	00:14	04:00	03:17	04:00	05:29
	15.00 - 18.00	04:00	03:41	00:20	04:00	03:18	04:00	07:04
Barlow to Franklin	6.00 - 9.00	02:00	01:43	00:07	02:00	01:32	02:00	02:57
	9.00 - 15.00	02:00	01:46	00:18	02:00	01:34	02:00	05:16
	15.00 - 18.00	02:00	01:50	00:08	02:00	01:37	02:00	02:23
Franklin to Marlborough	6.00 - 9.00	02:00	02:13	00:11	02:00	01:54	02:00	03:42
	9.00 - 15.00	02:00	02:18	00:11	02:00	01:54	02:00	03:24
	15.00 - 18.00	02:00	02:27	00:22	02:00	02:02	02:00	06:09
Marlborough to Rundle	6.00 - 9.00	03:00	02:31	00:10	03:00	02:15	03:00	03:46
	9.00 - 15.00	03:00	02:32	00:09	03:00	02:12	03:00	03:06
	15.00 - 18.00	03:00	02:37	00:16	03:00	01:45	03:00	05:10
Rundle to Whitehorn	6.00 - 9.00	02:00	01:47	00:33	02:00	01:28	02:00	05:29
	9.00 - 15.00	02:00	01:50	00:47	02:00	00:55	02:00	09:43
	15.00 - 18.00	02:00	02:00	02:20	02:00	01:25	02:00	30:49

Statistical Analysis for the Two Time Points

The statistical analysis of the two time points indicates that the average headway during the off-peak time is higher than the scheduled headway for both the inbound and outbound directions for lower headways of 3-5 minutes (Tables 5 and 6). For the inbound direction at the Bridgeland station, the SD of the headway exceeds two minutes; and, at the Marlborough station, the SD exceeds 1.30 minutes in most periods of the day. However, the average scheduled headway does not show a significant difference from the actual headway at both time point stations. In the outbound direction, there is a SD of more than three minutes at both stations during the off-peak times of the day.

Table 5: Statistical Analysis of Headways at the Two Time Points (Inbound Direction)

		Mean		SD	Minimum		Maximum	
	Time	Schedule	Actual	Actual	Schedule	Actual	Schedule	Actual
Bridgeland	Scheduled Headway of 3 to 5 minutes							
	06.00 - 09.00	4:27	4:33	1:19	4:00	2:03	5:00	7:36
	09.00 - 15.00	4:25	5:11	2:00	3:00	2:19	5:44	12:50
	15.00 - 18.00	4:26	4:48	2:30	4:00	1:56	5:00	19:57
	Scheduled Headway of 6 to 10 minutes							
	06.00 - 09.00	6:48	6:53	2:35	6:00	1:55	10:00	21:13
	09.00 - 15.00	9:18	9:25	2:46	6:00	1:57	10:00	25:07
	15.00 - 18.00	7:18	7:19	2:53	6:00	1:01	10:00	24:39
Marlborough	Scheduled Headway of 3 to 5 minutes							
	06.00 - 09.00	4:24	4:28	1:26	4:00	1:57	5:00	10:47
	09.00 - 15.00	4:32	5:24	1:51	3:00	2:12	5:20	10:29
	15.00 - 18.00	4:27	4:41	2:18	4:00	1:44	5:00	19:29
	Scheduled Headway of 6 to 10 minutes							
	06.00 - 09.00	6:54	6:52	1:52	6:00	2:16	10:00	12:30
	09.00 - 15.00	9:21	9:24	2:39	6:00	1:55	10:00	24:58
	15.00 - 18.00	7:10	7:11	2:49	6:00	0:36	10:00	24:03

Table 6: Statistical Analysis of Headways at the Two Time Points (Outbound Direction)

		Mean		SD	Minimum		Maximum	
	Time	Schedule	Actual	Actual	Schedule	Actual	Schedule	Actual
Bridgeland	Scheduled Headway of 3 to 5 minutes							
	06.00 - 09.00	4:15	4:26	1:38	3:00	2:07	5:00	9:12
	09.00 - 15.00	4:25	5:34	3:16	4:00	2:35	5:29	17:49
	15.00 - 18.00	4:18	4:59	2:31	3:00	1:54	5:00	19:31
	Scheduled Headway of 6 to 10 minutes							
	06.00 - 09.00	6:47	6:39	2:20	6:00	2:06	9:00	13:36
	09.00 - 15.00	9:37	9:37	3:19	6:00	1:29	10:00	35:16
	15.00 - 18.00	6:39	6:43	2:57	6:00	2:18	9:00	30:05
Marlborough	Scheduled Headway of 3 to 5 minutes							
	06.00 - 09.00	4:15	4:21	1:40	3:00	1:57	5:00	10:08
	09.00 - 15.00	4:24	5:20	3:19	4:00	1:53	5:16	19:53
	15.00 - 18.00	4:18	4:43	2:16	3:00	1:54	5:00	13:40
	Scheduled Headway of 6 to 10 minutes							
	06.00 - 09.00	6:39	6:35	2:26	6:00	2:15	9:00	13:16
	09.00 - 15.00	9:38	9:51	3:41	6:00	1:48	10:00	38:23
	15.00 - 18.00	6:49	6:30	2:54	6:00	1:47	9:00	16:49

CONCLUSION AND RECOMMENDATIONS

In this research, the NE line of Calgary Transit's LRT system was analyzed. The delay at each railway station was analyzed for both the inbound and outbound directions. The most critical sections of the line were identified and examined to understand the reasons for delays. The headway ratio (HWR) – the actual headway to the scheduled headway – was used to identify the reliability trend of operations along the line. The gap between trains was used to identify the uniformity of train departures. The variation of HWR within different time periods shows the non-reliability of train operation: a lower HWR in the CBD section can lead to some safety issues. The travel time variations and cumulative travel times along the line were used to show the necessity of rescheduling the LRT line.

The heterogeneity of passenger demand causes delays in LRT operation. This was especially evident in the analysis of inter-station delays, where the delay due to higher dwell times at some stations was clearly identified.

Necessary improvements to LRT operations are identified in two categories: improvement to the existing schedule and monitoring and improvement of operations.

Improvements to the Existing Schedule

For both inbound and outbound directions, more than 65% of the trains start one or two minutes delayed with respect to the scheduled time. When inbound trains reach the Bridgeland station, 45% are running behind either one or two minutes; however, across the CBD section, around 30% and 25% of the trains are delayed more than 3 minutes in the inbound and outbound directions, respectively. In the existing scheduling, only the two end stations of the CBD section are being considered; nevertheless, the delays at the middle stations of the CBD section affect the total travel times of trains. It is proposed that:

- Data on the dwell time at each station should be obtained, so that the scheduled inter-station travel times can be better estimated. (The currently available electronic devices could be upgraded for identifying the arrival and departure times of the trains at each station.)
- The demand variation and peak hour demand should be considered in scheduling. The headway of trains should depend on the demand of passengers with respect to the time of the day.
- Since the statistical analysis of travel time shows the inconsistency between the allocated travel times in the schedule and the real-time operations, the actual inter-station running times of the trains should be considered in developing the schedule. In particular, the travel time across the 7th Avenue should be studied and monitored separately.

Monitoring and Improvement of Operations

While around 10% of the trains depart early, 30% are delayed by more than one minute at Bridgeland in the inbound direction, and 20% of the trains depart early for the outbound direction. Early departures increase to forty percent from the Whitehorn station in the outbound direction. This indicates poor adherence to the schedule at the intermediate stations.

Early departures in the outbound direction should be corrected after monitoring of the departure times at the time points. The main reason for the early departures is the excess travel time provided in the schedule for the CBD section.

Since departure times are decided by the drivers, a protocol should be developed to maintain the scheduled times and prevent early departures. The Calgary Transit Control Centre should be associated with the protocol, since, in theory, all trains depart with the permission of the Control Centre.

For lower headways, the system fails to maintain a constant gap between trains. This is explained by the delays and early departures of trains in certain sections. Since the objective of drivers appears to be to reach the end terminal on time, the headway is being neglected. It is proposed that:

- A mechanism and penalty system should be implemented to prevent early departures of trains and speeding outside the CBD sections.

- Since all three lines and other public transit services share the CBD 7th Avenue corridor, there must be coordination between the LRT and other transit vehicles. The conflicts between the LRT, other traffic and pedestrians in the CBD section also has to be minimized. Updating of signal timing and signal synchronization will be an effective short-term solution.
- The time point at the Bridgeland station can be used to observe and control schedule adherence of the trains: it should be monitored regularly to improve the reliability of the system.

Solutions for Technical Issues in Operation

Delays due to signal breakdowns and doors getting stuck closed cannot be specifically identified with the existing data; however, according to Calgary Transit, these two issues cause delays in train operation. An efficient system should, therefore, be introduced to repair the signal systems during breakdowns.

Proper monitoring, control and continuous study will help to improve the reliability of the LRT system in Calgary. Since there are long-term proposals to expand the system to seven different lines, proper planning and control mechanisms are very important in providing a satisfactory service to the public in future.

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