January 2017

# Fuel Consumption Model Generation, Emission Estimation And Life Cycle Cost Analysis

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FUEL CONSUMPTION MODEL GENERATION,EMISSION ESTIMATION AND
LIFE CYCLE COST ANALYSIS

by

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A Thesis

Submitted to the Graduate Faculty

of the

University of North Dakota

In partial fulfillment of the requirements

for the degree of

Master of Science

Grand Forks, North Dakota
December
2017

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Ehtesam Rabbi
June, 2017

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ACKNOWLEDGEMENTS

First, I express my gratitude to the Department of Mechanical Engineering of the University of North Dakota, for giving me the opportunity to research and pursue a master degree here. My solemn gratitude to Dr. Cai Xia Yang who has been very kind and Guided to me. While being my supervisor in this academic period, she has enriched and trained me with vast knowledge and competitive skills.

I am very much grateful to committee members Dr. Marcellin Zahui and Dr. Surojit Gupta for their continuous support and advice.

I would like to thank Ali Rood at the City of Grand Forks for providing us the bus operation information, and suggestive explanation on data recording system.

To my parents - my idol of strength and courage

## ABSTRACT

There are a variety of transit bus sizes and types that are suitable for different types of cities, services, and operations. The size of a bus has a direct effect on the operating costs due to fuel consumption. Also, selecting bus size properly is very important for correct functioning and the quality and service level of public transportation. A decision on selecting bus size, fuel type and model year can only be made after considering the demand for each of the service routes on the system, fuel cost, and emission level. It is necessary to provide engineering resources to the local transit service so that they can assign a right size and fuel type of bus to a specific route from the existing bus fleet. Accurate evaluation of fuel consumption is best assessed by comparative testing over relevant drive cycles. In this thesis, a computational model is developed to compare the fuel economy of city transit buses fueled by gasoline and diesel engines considering each bus service route, passenger load variation, and fuel type and bus size. We further explore the potential advantages of each model year and size of the bus for a specific route. Using this automatic calculation process, Transit agencies can develop and design future enhancement of transit services, improve operation efficiency, and environmental benefits of adding additional services with limited funding. This thesis would also be useful to examine the accuracy of projected operating costs and to support decision making on bus purchasing.

# CHAPTER 1

# INTRODUCTION

The goal of this research is to assess City Area Transit (CAT) bus service and considering the environmental effect and sustainability issues; it is possible to optimize the current setting of the bus routing system and assignment. Transportation infrastructure and mobility is the key to a proper functioning of an active city. The city of Grand Forks has evolved to be more dynamic over the last few years thanks to the recent oil boom. With the rapid growth of the city, CAT has also accommodated the change in population and customer demand introducing new routes and continuous research and collaboration with the University of North Dakota. The University of North Dakota, as a college town has its obligation to the transit system to provide engineering insight and proper guideline.

The primary function of public transportation is to deliver accessibility of places where people go for activities in urban and regional areas. Demand for transit bus here in Grand Forks is determined by the number of people willing to commute by it. The success of a transit service also relies on the fact that how efficiently it has removed the necessity of a person owned vehicle. On the other hand, the transit authority also has to ensure that the emission from the fleet remains within the limit of the Environment Protection Agency (EPA) administered guideline. However, due to the budget constraint of the local transit authority, it is not always possible to measure accurate second by second emission data to monitor and regulate the emission data. Therefore, we need to use available tools and software to estimate the fuel consumption and emission from the real-world operating data.

The transit authority also has the responsibility to analyze the life cycle cost associated with the purchase cost of a transit bus and also cost-benefit analysis also has to be done to study the effect of a particular powertrain has superiority over the conventional drivetrain technology. So, a model is necessary to evaluate the life cycle cost of any given powertrain technology and help the transit agency to make purchase and procurement decision easier.

## 1.1 Background

Transit buses provide service on a repetitive, fixed-schedule, along with a specific fixed route, with planned bus stops to pick up and deliver passengers to specific locations; each fixed route trip serves the same origins and destinations. Grand Forks is a small city with a population of 69,179 (approx.). Due to moderate population and harsh weather variation, it is very important to have an efficient transit bus network operation.

CAT as the public transportation provider for Grand Forks, ND and East Grand Forks, MN, provides a multi-modal system of transportation resources by developing, maintaining, and supporting the development and delivery of public transportation services. These services will be geared toward improving the quality of life for residents and increasing the economic vitality of Grand Forks and East Grand Forks. Public Transportation first started in 1904, running from downtown Grand Forks to the University of North Dakota campus. An estimated 300 people rode the streetcar daily, and at times reached a peak of 800 passengers per day. The Street Railway Company extended additional streetcar lines to Lincoln Park, Riverside Park, the Fairgrounds, and East Grand Forks by 1913. In 1930 the Street Railway Company purchased two public transportation buses and later converted to an all bus fleet in 1934. The City took over operation of public transit services in the mid-1970 and continued to operate in that capacity today [1]. Currently, City Area Transit has four gasoline-fueled buses (25-feet), five diesel-fueled buses (two 30-feet, three 35-feet), and two diesel-electric buses (35-feet), and serves thirteen fixed routes and two tripper route within Grand Forks and East Grand Forks area as shown in Table 1 in the next page.

CAT operates on thirteen routes; six days a week over the year. Ten of them are interconnected with each other whereas route 3, route 5 and the night route are the only individual routes. Connected routes are route 1-2, route 4-6, route 8-9, route 10-11 and route 12- 13. According to geographic information system(GIS), these routes are also clustered into few subdivision. For example, route 1 and route 3 went through the residential area. Route 4, Route 6 and Route 8 went through University Avenue. Route 5, route 9, route 10 and route 11 went through both freeway and residential area. Finally; route 12 and route 13 went through freeway. Route 4, 6 and 8 has the highest stop sign besides the frequent stop and go pattern during the fall and spring semester. The residential area has designated stop sign with a speed limit of 25 miles per hour.

Given the magnitude of city dwellers, the transit bus has a low to moderate sitting arrangement for the passengers. All the 25-feet gasoline buses are equipped with a seating arrangement for 21 people. Two 30-feet diesel buses have 26 seats each, and finally, five of the 35-feet diesel buses has the seating arrangement for 30 passengers. Besides all the diesel buses has front hydraulics to lower the bus for disabled and old passengers as well as enhanced sitting room for children and wheelchair if needed. There is also standing room for passengers in the 35-feet diesel buses. However, the possibility of a bus to be overloaded in any given route is very unlikely.

Table 1.1: CAT existing fleet

| Bus No. | Year | Model | Manufacturer | Fuel Type | Seats | Standing | Annual Fuel | Annual Mileag | AVG | Route Assign |
|---|---|---|---|---|---|---|---|---|---|---|
| 91 | 2009 | 25 ft. | Chevy Arboc | Gasoline | 21 | 0 | 3,150 | 21,510 | 6.83 | 1, 2 |
| 112 | 2011 | 25 ft. | Chevy Arboc | Gasoline | 21 | 0 | 5,612 | 41,317 | 7.36 | 1, 2 |
| 114 | 2011 | 25 ft. | Chevy Arboc | Gasoline | 21 | 0 | 5,822 | 44,011 | 7.56 | 10, 11 |
| 113 | 2011 | 25 ft. | Ford E-450 | Gasoline | 21 | 0 | 6,749 | 48,582 | 7.2 | 12, 13 |
| 31 | 2003 | 30 ft. | Gillig | Diesel | 26 | 21 | 4,377 | 31,519 | 7.2 | 8, 9 |
| 42 | 2004 | 30 ft. | Gillig | Diesel | 26 | 21 | 6,094 | 29,681 | 4.87 | 8, 9 |
| 976 | 1997 | 35 ft. | New Flyer | Diesel | 30 | 20 | 4,571 | 23,254 | 5.09 | Trippers, Night |
| 105 | 2010 | 35 ft. | New Flyer | Diesel | 30 | 20 | 8,167 | 37,376 | 4.58 | 3, 4, 5, 6 |
| 106 | 2010 | 35 ft. | New Flyer | Diesel | 30 | 20 | 11,028 | 47,707 | 4.33 | 3, 4, 5, 6 |
| 103 | 2010 | 35 ft. | New Flyer | Diesel-Electric | 30 | 20 | 7,146 | 40,254 | 5.63 | 3, 4, 5, 6 |
| 104 | 2010 | 35 ft. | New Flyer | Diesel-Electric | 30 | 20 | 6,121 | 37,226 | 6.08 | 3, 4, 5, 6 |

## 1.2 Research Problem

Apart from the remarkable amount of time, money and resources spent on a self-sustaining transit service, one has also kept an aspect in account that transit bus is often considered to be for lower class people, irregular and always over crowded. A popular misconception among the city dwellers about public transport is electric buses are more environment-friendly than the conventional gasoline and diesel counterpart. Many people also believe that city should change to accommodate the transit system which is just as opposite from the reality. Therefore, it's a challenge for the city to convince the people about transit service and its effect on the environment.

There was not enough engineering analysis before the transit bus assignment to each route from the transit authority. Most of the bus to route assignment were done based on experience. So, there was a need for a thorough investigation from an engineering point of view to justify the assignment done by CAT. Moreover, there was a need for a mathematical model.

This City of Grand Forks runs a scheduled maintenance on their bus fleet spending about $130,000 annually. However, as these buses get older, their maintenance cost increases, raising the need of buying a new bus that would require less maintenance attention, and would cost less by running more efficiently consuming even less fuel. The City of Grand Forks is adding one new bus into their fleet every year on average, and eliminating the least financially beneficial one. Therefore, the need of recommendations on what kind of bus to purchase is required. To make a decision regarding those recommendations, a study based on data analysis and calculations has to be made.

Additionally, the current transit bus program needs to have scientific research to support its mission statement by being able to provide better services for the city residents with the lowest costs possible. To provide that, our research is presenting the important elements for achieving that goal such as creating an algorithm to distribute buses over routes in a specific arrangement that would provide the best efficiency for fuel solutions. Also, generate equations for cost reduction to run the buses including variables like fuel cost and cost of repair.

Finally, the research includes a study of methods of reducing harmful gas emissions. Which is important to satisfy the Environmental Protection Agency (EPA) standards and regulations that claim to enable the production of a new generation of clean vehicles, through reduced greenhouse gas (GHG) emissions and improved fuel use [2].

## 1.3 Research Objective

The primary objective of this study is to analyze the current CAT service and optimize the setting where necessary. To reach that goal first, we need to develop a mathematical model to estimate the fuel consumption of each mode of the bus for each route. Secondly, we need to incorporate all kind of cost associated with transit service and create our second model. Then we compare both the model and filter out the best possible combination to ensure perfect assignment of the bus to each route.

We also need to develop a life cycle cost model for the CAT authority. For any local and regional transit service, life cycle model is a vital tool to estimate the cost-benefit analysis during budget and procurement. It helps to decide what mode of the vehicle is the most suitable for a defined life cycle. It also the user to compare the cost benefit between conventional engine like diesel and gasoline engine with alternative powertrain like CNG, electric or hybrid bus.

Since we are not calculating the emission and fuel consumption using the on-board measuring unit, we need to estimate fuel consumption and emission using available simulation software and open-source database. Emission database has to be set up for the state and the city individually and calculate the emission from the transit bus. Therefore, we can estimate the effect of replacing a kind of transit bus with an alternative drivetrain.

## 1.4 Research Design

The thesis organized to carry out in sequential phases where each phase describes its scope and motivation.

### *1.4.1 Identification of the current CAT system*

The study is launch with the overall discussion of the current transit phenomena based upon available literature review and observation made so far in the field of transportation. This is the part where we investigate the problem in the light of research and try to develop a methodology of analysis and data acquisition.

### *1.4.2 Generating two models*

At this phase, we develop two separate models. The first one is fuel consumption model and the second one is preferability index model. This phase also includes the comparison between the models and a new assignment of the bus to route based on the conclusion made from the models. Finally, all the results from the analysis will be evaluated an forwarded to the CAT for future implementation and development.

## 1.5 Literature Review of Existing Fuel Consumption Calculation Method

There has been some method adopted to estimate fuel consumption for a vehicle of different powertrain and size. From commercial heavy-duty truck to lightweight passenger's car; all modes of the vehicle were subjected to some studies to estimate their fuel consumption and emission modeling. Most common input variables to these models are the vehicle tractive power and speed or vehicle specific speed.

A theoretically based fuel consumption model was developed in [3] where the amount of exhaust emission was estimated. This model was compared with an existing empirical model that has been derived through experiment. The model is represented by the following equations,

$$F_w = (m + m_j)a + \frac{1}{2}c_d A\rho e^2 + mg\, c_r cos\theta + mgsin\theta \quad (1)$$

$$ft = ft_{idle} + \frac{\delta}{\eta_t \epsilon H_g}(mg(c_r cos\theta + sin\theta) + (m + m_j)av + \frac{1}{2}c_d A\rho v^3) \quad (2)$$

Here $m$ is the mass (kg), $m_j$ is the equivalent mass of the inertia for the moveable parts in the powertrain (kg), $a$ is the vehicle acceleration (m/s$^2$), $c_d$ is the air drag coefficient, $v$ is the vehicle speed (m/s), $c_r$ is the rolling resistance, $\rho$ is the air density (kg/m$^3$), $g$ is the gravity acceleration (m/s$^2$), $\theta$ is the road slope, $\epsilon$ is the brake thermal efficiency of the engine, $\eta_t$ is the total transmission efficiency, $H_g$ is the heat equivalence of gasoline (J/cm$^3$), $ft_{idle}$ is the idling consumption rate (cm$^3$/s) and $ft$ is the instantaneous fuel consumption rate (cm$^3$/s). This model was based on the assumption that fuel consumption for any vehicle is zero when total resistance along the direction of movement is less than or equal to zero.

Another fuel consumption model based on the instantaneous power requirement was generated from chassis dynamometer testing [4]. This model is expressed by

$$F(t) = \begin{cases} \alpha_1 + \beta_1\, P(t), & P(t) > 0 \\ \alpha_1, & P(t) \le 0 \end{cases} \quad (3)$$

Where $F(t)$ is the instantaneous fuel consumption rate (dm$^3$/s), $\alpha_1$ is the vehicle

Idling fuel consumption rate (dm$^3$/s), $\beta_1$ is the vehicle fuel consumption rate

(dm$^3$/s/kW) And $P(t)$ is the instantaneous tractive power (kW). As the vehicles condition changes, the vehicle parameters also change with time. However, this model is incapable to calculate fuel consumption rate during stop and start the activity.

Australian Road Research Board developed a fuel consumption model based on the model of which is represented by

$$F(t) = \alpha_2 + \beta_a P_a(t) + \beta_b P_c(t) \quad (4)$$

Here, $F(t)$ is the instantaneous fuel consumption rate(dm$^3$/s), $\alpha_2$ is the vehicle idling fuel consumption rate (dm$^3$/s), $P_c(t)$ is the total drag power exerted while travelling at a constant speed (kW), $P_a(t)$ is the total engine and drag power (kW), $\beta_a$ and $\beta_b$ are vehicle specific power parameters (dm$^3$/s/kW).

A study for diesel fueled vehicle based on powertrain and road load parameter is presented in [5]. Major components of this model are engine maximum torque map, engine friction and efficiency, vehicle transmission and vehicle road load parameter. Including this parameter, the fuel consumption model can be presented as:

$$FR = \frac{1}{LHV} \times \left(\frac{K \times N \times V_d}{2000} + {}^{P}/_{\eta}\right), \quad where, \quad k = \frac{1}{\eta_i} fmep \quad (5)$$

Where, $N$ is engine speed in revolution per second, $V_d$ is the engine displacement in liters, $LHV$ is the fuel lower heating value in kJ/k, $\eta_i$ is the indicated engine efficiency, $k$ is engine friction in kPa,, $fmep$ is the friction mean effective pressure in kPa and P is the sum of the vehicle tractive power and accessory power (kW).

The sum of the required instantaneous power demand can be calculated as

$$P = \frac{P_{trac}}{\eta} + P_{acc} \quad (6)$$

$$P_{trac} = Mg\,(v\,C_{R0} + v^2 C_{R1}) + \left(Mg\,C_{R2} + \frac{A_f C_D\,\rho_{air}}{2}\right) v^3 + Mv\,(a + gsin\theta) \qquad (7)$$

where $P_{trac}$ is the sum of the tractive power (kW), $\eta$ is the total transmission efficiency, $P_{acc}$ is the accessory power (kW), $M$ is the vehicles mass (kg), $g$ is the gravity acceleration (m/s$^2$), $v$ is the speed of the vehicle (m/s), $C_R$ is the rolling loss coefficient, $A_f$ is the frontal area of the vehicle (m$^2$), $C_D$ is the air drag coefficient, $\rho_{air}$ is the air density (kg/m$^3$), $a$ is the vehicle acceleration (m/s$^2$) and $\theta$ is the road slope (rad).

All the above fuel consumption model presented considered vehicle tractive power or speed alongside with acceleration and road slope as an input variable. These models were generated without the aid of any software or conventional database.

The model described in equation 5, and 7 has been tested for a wide range of diesel vehicles and confirmed to have an accuracy within 10% of the measured value.

Influence of the key factors like speed, acceleration and road grade on fuel consumption for diesel and hydrogen fuel cell buses under the real-world operating condition is explored in [6]. Vehicle specific power approach was taken for this study which integrates the effect of speed, acceleration, and road grade into a single parameter to justify the substantial amount of variability in fuel consumption. However, this model does not include the passenger load. Vehicle, specific speed approach, was also used in [7] to compare integrated second by second measured fuel consumption and $NO_x$ emission estimation.

The more conventional way of studying the fuel consumption and emission estimation is to place an onboard testing equipment like autologous 5- Gas Analyzer, Handheld Garmin ETrex Global Positioning System (GPS) and a Krestel 4000 Pocket Weather Meter [8]. This method of study estimates the most accurate emission of the greenhouse gasses and particulate matter, but output varies with the change of on-road testing device and data acquisition method. The study also concludes that hybrid diesel-electric bus over a conventional diesel bus is not an effective solution for reducing air pollution.

Recently, development of standard drive cycle has been studied based on the premise that fuel consumption emission is most accurate when mean tractive force is considered [9], since drive cycles have the same vehicle excitation in the mean tractive force. There has been different technique adopted to construct drive cycle. The first approach is to select micro-tips between two successive stops and assemble of the driving cycle [10]. Another approach is to a model-based approach where the speed acceleration frequency distribution are made similar to the real world driving data [11]. Finally, a Markov chain approach has been used for generating representative driving cycles from real-world driving data in a more compact manner [12-13].

Some studies have been done using the ADVISOR simulation software which also uses these standard drive cycle to estimate energy consumed specifically by the electric vehicle and hybrid electric vehicle [14-16]. This is a user-friendly simulator which works on a combined backward, forward approach designed and developed by National Renewable Energy Limited (NREL). Apart from analyzing the sensitivity of fuel economy to vehicle key parameter, it can also calculate the effect of hybridization on the conventional gasoline and diesel vehicle [17]. An important cost benefit analysis of hybrid and city buses in the fleet was done using ADVISOR in [18]. The notable outcome of this study was that the capital and energy storage system costs of city buses are the most critical factors for improving the cost efficiency of these alternative city bus configuration.

Most of the studies mentioned above was done primarily with chassis dynamometer testing or from drive cycle analyzing. However, in-service testing with passengers' loads would give more accurate data. Clean air technologies did this kind of experiment for the first time with onboard portable emission-measuring system during revenue service [19], and it was concluded in-service emissions measurement during revenue service was a very feasible approach to transit bus emission measurement. In this study, it was also found out that testing of a large number of the vehicle for a relatively long time is necessary to understand and characterize emissions from a particular fleet of the vehicle due to unrepeatable real world driving condition.

With the invention of state of the art portable instruments, work has been done on measuring real world exposure concentration in public transit microenvironment [20-21]. $PM_{2.5}$ concentration was compared among MTR train, large transit buses and trams in [20]. In recent times, data generated from GPU, ECU and PEMS are combined together and valid data recovered are used for calculating fuel use and emission of diesel side-loader refuse trucks [22].

To avoid these intricacies and make budget and procurement easier for transit agencies, a local database is created using West Virginia University generated Integrated Bus Information System (IBIS). IBIS has developed a set of convenient tool for evaluating the pollutant emission, greenhouse gases, and fuel economy of transit buses. It contains both searchable database of transit vehicle emission test data and a transit fleet emissions fleet emission inventory.

There has been a number of research regarding the cost benefit analysis of different modes of buses in the light of transportation research. Five different full size hybrid and electric city bus configuration were put to side by side comparison in a research conducted in Aalto University in [23] for cost effectiveness and energy consumption analysis. It was found out that the capital and energy storage cost have the major impact on the cost effectiveness of hybrid and electric buses. Electric city buses have huge potential to decrease $CO_2$ emission although high purchase cost is the primary obstacle to reckon with.

In another study in [24] different alternative for electric city bus were evaluated to compare the impact on the total energy efficiency of the buses based upon their configuration and drive cycle. In this study, the powertrain solution with two permanent magnet motors had the best performance in the total energy efficiency and motor efficiency.

In a fuel cell hybrid bus program in Argonne National Laboratory, system energy data analysis has revealed high-efficiency performance due to regenerative braking and plug-in configuration [25]. There has been an enormous success in lowering $NO_x$ and PM emission using selective catalytic reduction (SCR) and diesel particulate filter (DPF) retrofitted with truck. In [26] emission rates were lower than 90% than the rates of older trucks without these controls. Some of the studies concentrates on fuel consumption during driving and idling by published emission factor [27]. This study also confirms that cost of emitting criteria air pollutant (CAP) and greenhouse gases (GHG) are not trivial relative to the magnitude of the direct operational cost.

# CHAPTER 2

# FUEL CONSUMPTION MODEL

Fuel consumption has been shown to be the fundamental criteria to properly judge fuel efficiency improvements; our first step would be to design a robust and reliable fuel consumption model. Fuel Consumption calculative model for the twelve route is based upon engine power demand, P for a travel distance of that specific route distance, diesel fuel density, $\rho_{diesel}$ (kg/l) ($\rho_{gasoline}$ in the case of gasoline) and specific fuel consumption, SFG (g/KW). Fuel consumption is presented in liter per 100 kilometers.

A transit bus power demand depends on both on its physical properties and geometric parameter [28]. The geometric parameter consists of frontal area shape, road grade, road material types. The power demand of transit bus can be separated to auxiliary power demand and tractive engine power demand. Tractive engine power demand can be calculated from the acceleration force, rolling resistance, aerodynamic drag, and force due to gravity. On the other hand, auxiliary power demand is calculated based on the weather pattern, time of the day and equipment duty cycle. This consumption model is created using a limited portion of methodology generated by Yang and Bibeau [29].

Our primary concern is to analyze all the gasoline and diesel bus and learn how the fuel economy changes across the different route. For this purpose, we developed a detailed calculation on excel to calculate fuel consumption and eventually to obtain fuel economy. Currently, CAT is operating with four 25 feet gasoline bus; two 30 feet diesel bus, three 35 feet diesel bus, and two diesel-electric hybrid buses.

## 2.1 Calculation of Fuel Consumption

The fuel consumption model for selected representative routes is constructed based on the engine power demand, *P* (kW), the specific fuel consumption, *SFC*(g/kW), corresponding travel distance, *DS*(km) and diesel fuel density $\rho_{diesel}$(kg/l). The fuel consumption value is calculated in liter per 100 kilometers. The equation for fuel consumption model is given as follows:

$$Fuel = P \times SFC/(\rho_{diesel} \times 1000)/DS \times 100) \quad (8)$$

A transit bus engine power demand P-dependent on the bus characteristics, such as frontal area and frontal area shape, bus speed and acceleration, geometric road parameters, such as road grade, facility types, surface material types, and power demand from transit bus accessories.

The power requirement is based on the propulsive forces acting on a vehicle wheels. The propulsive forces are obtained by using basic Newtonian mechanics. The model estimates total power required to overcome resistance forces, to run vehicle accessories, and to overcome internal engine friction. The total power required from the engine, in conjunction with power efficiency factors, are used as the basis for estimating fuel consumption. The governing equations are given as follows:

$$P = (V/3.6\ [ma + F\_R + F\_W + F\_D\ ])/1000 + AP \quad (9)$$

$$E = \int_0^t P dt/3600 \quad (10)$$

Where,

$$F_R = C_r\ mg \cos\theta \quad (11)$$

$$F_W = mg \sin\theta \quad (12)$$

$$F_D = \frac{1}{2}\rho C_d A_f (V + V_W)^2 (1/3.6)^2 \quad (13)$$

Table 2.1 contains all the parameter and values used for the model. $V$ is the vehicle speed (km/h), $m$ is the actual vehicle mass (kg), $a$ is the vehicle acceleration (m/s$^2$), $F_R$ is the rolling resistance force (N), $F_W$ is the gravitational weight force (N), $F_D$ is the aerodynamic drag force (N), $AP$ is the auxiliary power demand (kW), $E$ is the total energy demand (kWh), $t$ is time (s), $C_r$ is the rolling resistance coefficient, $g$ is the acceleration due to gravity (m/s$^2$), $\theta$ is the grade angle of the road (degree), $\rho$ is the air density (kg/m$^3$), $C_d$ is the aerodynamic drag coefficient, $A_f$ is the frontal bus area (m$^2$),and $V_w$ is the head-wind speed (km/h).

Table 2.1 Values of parameters used in fuel consumption model

| **Parameter** | **Value** | **Unit** |
|---|---|---|
| Air density, $\rho_{air}$ | 1.29 | kg/m$^3$ |
| Bus front area, $A_f$ | 7.84 | m$^2$ |
| Drag coefficient, $C_d$ | 0.65 | n/a |
| Roll resistance coefficient, $C_r$ | 0.008 | n/a |
| Curb weight of 25-ft gasoline | 4023.36 | kg |
| Curb weight of 30-ft diesel | 9734.08 | kg |
| Curb weight of 35-ft diesel | 12360.38 | kg |
| Assumed weight per passenger | 68 | kg |
| Road grade | 0 | degree |
| Specific fuel consumption, *SFC* | 242 | g/kW |
| Diesel fuel density, $\rho_{diesel}$ | 0.85 | kg/l |

One unique aspect of the transit service here is all the routes are designed so that a bus takes an average of 25 minutes to travel the entire route. So for an even comparison between the buses, we select similar kind of data and analyze the variation between the mpg in a different route and also the variation within the mpg for every kind of bus. Using the fuel consumption model, we extracted data for analysis and comparison, passenger load was selected as an average passenger of 10 based on ridership data provided by CAT. The bus travel speed was 30 mile per hour based on real operating average speed. The comparison results are summarized in Table 2.2.

Table 2.2. Comparison between three modes of buses for 12 routes with fixed average velocity of 30 mph and passenger load of 10

| Route # | 25 Ft Gasoline(L/100km) | 30 Ft Diesel(L/100 km) | 35 Ft Diesel(L/100 km) |
|---|---|---|---|
| 1 | 33.36 | 47.70 | 47.52 |
| 2 | 41.19 | 51.47 | 58.66 |
| 3 | 43.8 | 54.70 | 62.39 |
| 4 | 41.19 | 51.47 | 58.66 |
| 5 | 34.59 | 43.24 | 49.31 |
| 6 | 40.07 | 50.05 | 57.09 |
| 8 | 35.48 | 44.38 | 50.58 |
| 9 | 41.19 | 51.47 | 58.66 |
| 10 | 36.87 | 46.12 | 52.50 |
| 11 | 35.91 | 44.89 | 51.13 |
| 12 | 38.37 | 48.00 | 54.70 |
| 13 | 40.07 | 50.05 | 57.09 |

From Table 2.2, it can be seen that 25 feet gasoline buses are the ones with highest fuel economy, and 30 feet diesel buses and 35 feet diesel buses are consecutively next to its fuel economy. Which is unusual since Carnot cycle which governs heat engine, suggest, the more the efficiency of the system relies on combustion, the worse the efficiency of the system. As for diesel-electric and diesel engine have similar overall drive-train efficiency whereas gasoline buses higher average fuel economy than the diesel. This is due to the engine efficiency decline with the age of bus. All the gasoline buses are relatively new and purchased between 2009 and 2011, compared to two diesel engine buses purchased around 2003-2004. Figure 2.1 shows fuel consumption comparison.

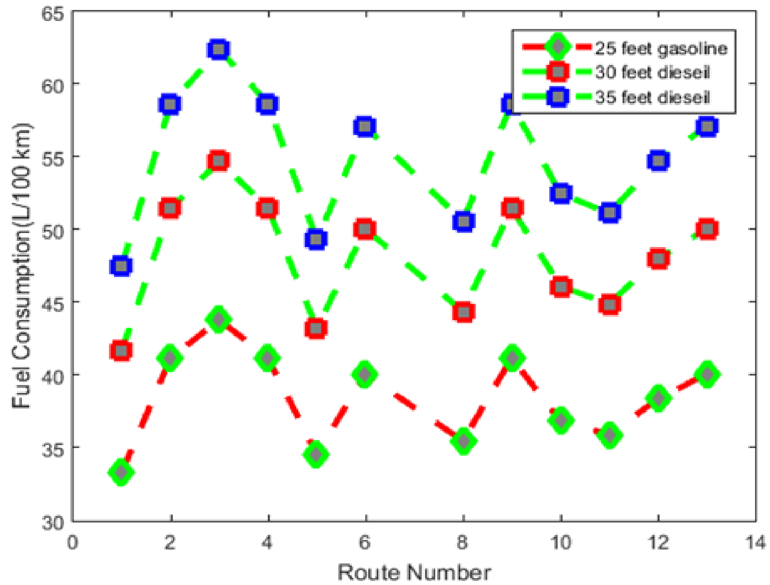


Figure 2.1 Fuel consumption comparison for three buses in every routes

These results are found within the range of suggested fuel economy from fuel economy test run on simulated central business bus district, arterial and commuter course . Next step is to reassign the buses based on the service hour per year or the length they used to travel in a day. Few routes are connected together to form a big closed loop in which they travel all the day long. For example, route 1 and 2 are connected so that a transit bus only change the route name on its display when it finishes its cycle and enters into the second loop. Same goes for routes 8 and 9, routes 4 and 6, routes 10 and 11 and routes 12 and 13. Therefore, when assigning the transit bus, we consider the connected route as a part of a bigger route and add both distances of a connected route for calculating total distance.

Diesel buses being big and noisy, we cannot run it into the residential areas. Keeping all these things into consideration, we reassign the bus route along twelve routes by the terms and condition of Cities Area Transit.

From the calculation showed in Table 1.1, it can be seen that the longest routes are connected routes 1 and 2. We assign one 25 feet gasoline bus for these routes based on results shown in Fig.1. One gasoline bus is good enough to provide satisfactory 12 times a day service into the routes mentioned above. Similarly, we assign the other two gasoline buses for the next largest individual route 5 and connected routes 12/13 and 10/11. From the two 30 feet diesel buses, we assign one for route 3, and the other one will be used for night route and tripper service. Then, we allocate one 35 feet diesel-electric bus for Route 4/6 and one 35 feet diesel bus for routes 3.

## 2.2 Model Validation

In order to validate our model we need to compare our results with the data provided by CAT in table 1. First of all we extract all the data from the miles per gallon column and convert it to liter per 100 km to compare with the fuel consumption model generated output in table 2.2.

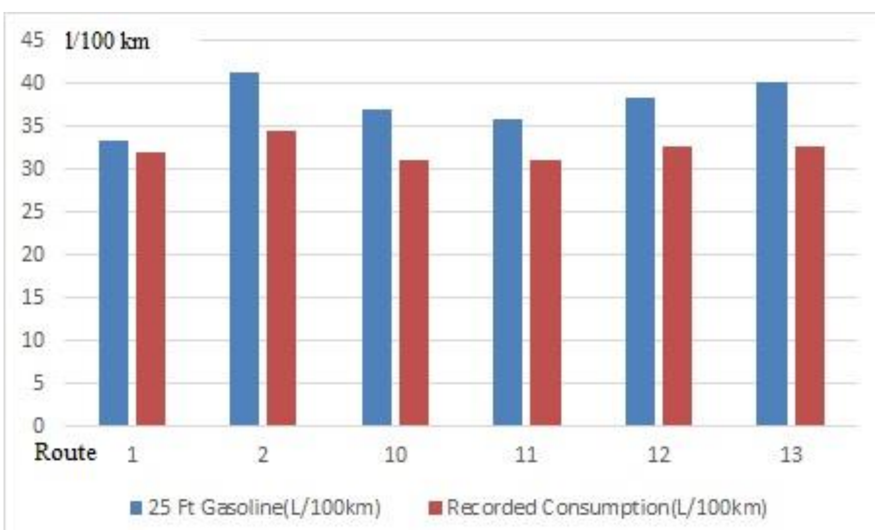


Figure 2.2 Model validation for 25 feet gasoline bus

A fuel economy test A Fuel Economy Test was run on simulated central business district, arterial, and commuter courses. The results were 54.07 L/100 km, 49.31 L/100 km, and 30 L/100 km mpg respectively. The fuel consumption model generated result is well within the range of the simulated output.

The figure 2.2 represents the comparison among the routes where 25 ft. gasoline bus is in operation. The results obtained from the fuel consumption model is very close to the transit dataset. However there are some anomaly in route 2 and route 13 due to the fact that the consumption model incorporate average speed and passenger load whereas the dataset represent the overall fuel consumption of one year.

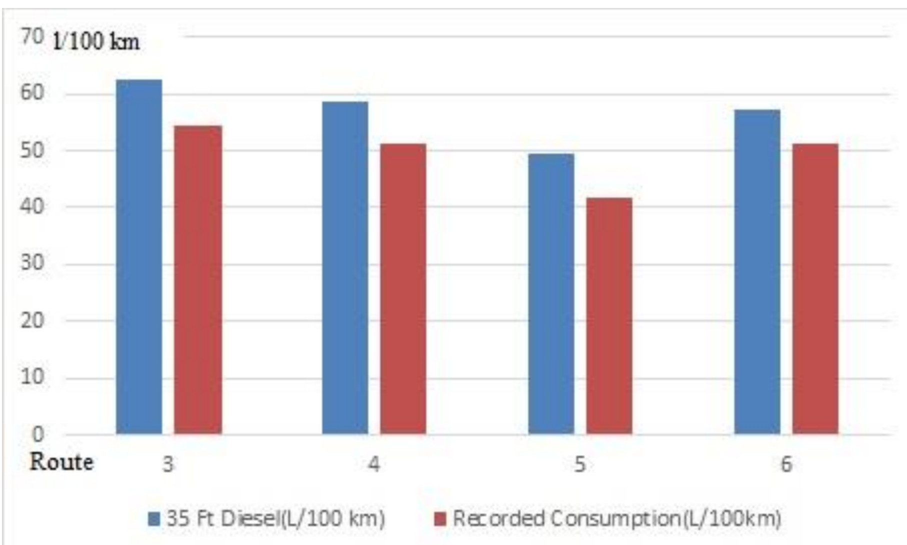


Figure 2.3 Model validation for 35 feet gasoline bus

Figure 2.3 represent the fuel consumption comparison for the 35 ft. diesel operated bus route. The fuel consumption model generated results forecast an identical amount of overshoot for route 3, 4 and 5 respectively with average of 54.85 L/100 km. The simulation results for 35 ft. diesel bus were 56.81 L/100 km and 46.30 L/100 km respectively with an overall average of 45.58 mpg.

The two 30 feet diesel buses cover route 8 and route 9 with an average annual fuel consumption of 45 L/100 km which resembles with the average annual fuel consumption of 48.62 L/100 km obtained from the model.

# CHAPTER 3

# PREFERABILITY INDEX MODEL

To validate the estimated fuel consumption model, a comparison is needed between the results obtained from the model with the existing data available from CAT service. Since, the calculated values of the average miles per gallon for each of the bus in the past year is available, only thing to calculate was the total number of miles a vehicle would travel annually if it were assigned to a given route, then divide that number of miles by the average fuel efficiency of the bus to determine the estimated number of gallons of fuel that the bus would consume if it were always assigned to that route. As CAT operates with diesel and diesel-electric bus alongside with conventional gasoline bus, it is necessary to convert gasoline and diesel-electric to diesel equivalent gallons for easier comparison between different bus types. Diesel Equivalent is simply a comparison of one fuel type to another based on how much energy is released by the combustion of diesel fuel.

## 3.1 Minimize Fuel Consumption

Minimizing the fuel consumption was one of the easiest results to analyze since the City of Grand Forks has already calculated values of the average miles per gallon that they were physically monitoring for each bus in the past year. Firstly, calculation needed to be done was to determine the total number of miles a vehicle would travel in a year if it were assigned to a given route, then divide that number of miles by the average fuel efficiency of the bus to determine the estimated number of gallons of fuel that the bus would consume if it were always assigned to that route. However, some of the busses use different types of fuel than others do making it difficult to draw a direct comparison between them. As such, we use Equations 3 and 4 to convert the number of gallons of base fuel into some Diesel-Equivalent Gallons (DEG) for easier comparison between different bus types. Diesel Equivalent is simply a comparison of one fuel type to another based on how much energy is released by the combustion of diesel fuel.

$$Anual\ Gallons\ per\ Year = \frac{Annual\ miles\ travelled}{average\ miles\ per\ gallon} \tag{14}$$

$$Annual\ DEG(gas)\ = \frac{Fuel\ Energy\ Content\ \left(\frac{btu}{gal}\right)}{Diesel\ Energy\ Content\ \left(\frac{btu}{gal}\right) x\ Annual\ Fuel\ (gal)} \tag{15}$$

Once these equations have been applied, we obtain the results listed in Table 3.1 below:

Table 3.1: Results of Fuel Consumption Calculation (DEG consumed annually)

| **BN/RN** | **91** | **112** | **114** | **113** | **31** | **42** | **976** | **105** | **106** | **103** | **104** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 4,450.0 | 4,129.5 | 4,020.3 | 4,221.3 | 5,110.0 | 7,554.8 | 7,228.3 | 8,033.2 | 8,497.0 | 6,535.0 | 6,051.3 |
| **2** | 3,602.4 | 3,343.0 | 3,254.5 | 3,417.2 | 4,136.7 | 6,115.8 | 5,851.5 | 6,503.1 | 6,878.5 | 5,290.2 | 4,898.7 |
| **3** | 6,780.9 | 6,292.6 | 6,126.2 | 6,432.5 | 7,786.7 | 11,512.1 | 11,014.5 | 12,241.0 | 12,947.8 | 9,958.1 | 9,221.1 |
| **4** | 3,602.4 | 3,343.0 | 3,254.5 | 3,417.2 | 4,136.7 | 6,115.8 | 5,851.5 | 6,503.1 | 6,878.5 | 5,290.2 | 4,898.7 |
| **5** | 8,224.5 | 7,632.3 | 7,430.4 | 7,801.9 | 9,444.4 | 13,962.9 | 13,359.4 | 14,847.1 | 15,704.3 | 12,078.1 | 11,184.1 |
| **6** | 3,708.3 | 3,441.3 | 3,350.2 | 3,517.8 | 4,258.3 | 6,295.7 | 6,023.6 | 6,694.3 | 7,080.8 | 5,445.8 | 5,042.8 |
| **8** | 4,185.1 | 3,883.7 | 3,781.0 | 3,970.0 | 4,805.8 | 7,105.1 | 6,798.0 | 7,555.0 | 7,991.2 | 6,146.0 | 5,691.1 |
| **9** | 3,602.4 | 3,343.0 | 3,254.5 | 3,417.2 | 4,136.7 | 6,115.8 | 5,851.5 | 6,503.1 | 6,878.5 | 5,290.2 | 4,898.7 |
| **10** | 4,026.2 | 3,736.2 | 3,637.4 | 3,819.3 | 4,623.3 | 6,835.3 | 6,539.9 | 7,268.1 | 7,687.8 | 5,912.6 | 5,475.0 |
| **11** | 3,890.2 | 3,610.1 | 3,514.6 | 3,690.3 | 4,467.2 | 6,604.5 | 6,319.1 | 7,022.7 | 7,428.2 | 5,713.0 | 5,290.1 |
| **12** | 3,867.2 | 3,588.8 | 3,493.8 | 3,668.5 | 4,440.8 | 6,565.5 | 6,281.7 | 6,981.2 | 7,384.3 | 5,679.2 | 5,258.9 |
| **13** | 3,708.3 | 3,441.3 | 3,350.2 | 3,517.8 | 4,258.3 | 6,295.7 | 6,023.6 | 6,694.3 | 7,080.8 | 5,445.8 | 5,042.8 |
| **night** | 2,949.0 | 2,736.6 | 2,664.2 | 2,797.5 | 3,386.4 | 5,006.6 | 4,790.2 | 5,323.6 | 5,630.9 | 4,330.7 | 4,010.2 |

$$Annual\ DEG\ (elec)\ = \frac{Annual\ Energy\ (kwh)\ x\ 3{,}412\ btu/kwh}{Diesel\ Energy\ Content\ (btu/gal)} \tag{16}$$

## 3.2 Minimize Emission

Within the emission produced by automobiles, there are several different gasses that are harmful to the environment that we want to keep track of: The most harmful of these are CO2 and $NO_x$

$CO_2$: Carbon Dioxide is largely harmless to humans but does contribute significantly to global warming.

$NO_x$: Mono-nitrogen oxides react with ammonia and moisture already present in the air to create Nitric Acid. This acid can if inhaled cause respiratory problems, bronchitis, and worsen heart disease.

First, we will show how the amount of $CO_2$ produced in a 1 year period by a given bus was calculated.

$$Annual\ DEG(gas)\ = \frac{Fuel\ Energy\ Content\ \left(\frac{btu}{gal}\right)}{Diesel\ Energy\ Content\ \left(\frac{btu}{gal}\right) \times Annual\ Fuel\ (gal)} \tag{17}$$

$$Annual\ DEG\ (elec)\ = \frac{Annual\ Energy\ (kwh) \times 3{,}412\ btu/kwh}{Diesel\ Energy\ Content\ (btu/gal)} \tag{18}$$

. Because we have multiple fuel type consuming buses, we need to convert all types to Diesel for easier comparison in further equations.

$$Aassenger\ Miles\ per\ DEG\ \left(Pass - \frac{mi}{DEG}\right) = \frac{Annual\ Passenger\ Miles}{Annual\ DEG} \tag{19}$$

Furthermore, the following table will provide all the information required for the equation givens

$$Btu\ per\ Passenger\ Mile\ \left(\frac{btu}{pass} - mi\right) = \frac{Annual\ DEG \times 138{,}000\frac{btu}{DEG}}{Annual\ Passenger\ Miles} \tag{20}$$

$$CO_2\ \left(\frac{g}{gal}\right) = \frac{44\ (CO2mw)}{12\ (Cmw) x\ 453.6\frac{g}{lb} \times Fuel\ Density\ \left(\frac{lb}{gal}\right) \times Fuel\ Wt\ \%\ Carbon} \tag{21}$$

$$Total\ CO_2\ (g) = \sum_1^{All\ fuels} \left(CO_2\ \left(\frac{g}{gal}\right) \times\ Annual\ Gallons\right) +\ Electricity\ (kwh) \times\ 600.6\ g\frac{CO2}{kwh5} \tag{22}$$

$$CO_2\ per\ Passenger\ Mile\ \left(\frac{g}{pass} - mi\right) = \frac{Total\ \mathbf{CO2}\ (g)}{Annual\ Passenger\ Miles} \tag{23}$$

Table 3.2: Fuel properties used in the analysis

| **Fuel** | **Energy (BTU/gal)** | **Density (lb./gal)** | **Weight% Carbon** | **CO g/gal** |
|---|---|---|---|---|
| **Diesel** | 138,000 | 7.1 | 87% | 10,274 |
| **Gasoline** | 114,000 | 6.0 | 85% | 8,482 |
| **LPG** | 91,330 | 4.4 | 82% | 6,042 |
| **LNG** | 73,500 | 3.2 | 75% | 4,017 |
| **CNG (DEG)** | 138,000 | 6.0 | 75% | 7,517 |
| **Kerosene** | 135,000 | 6.9 | 86% | 9,935 |
| **B20 Biodiesel** | 135,613 | 7.0 | 84% | 9,748 |

In order to calculate $CO_2$ emission, fuel properties in table 3.2 has to be considered. Once these calculations is performed, the results listed in Table 3.3 is obtained,

Table 3.3: Results of $CO_2$ emissions calculation (kg)

| BN/RN | 91 | 112 | 114 | 113 | 31 | 42 | 976 | 105 | 106 | 103 | 104 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 45.72 | 42.43 | 41.30 | 43.37 | 52.50 | 77.62 | 74.26 | 82.53 | 87.30 | 47.00 | 43.52 |
| 2 | 37.01 | 34.35 | 33.44 | 35.11 | 42.50 | 62.83 | 60.12 | 66.81 | 70.67 | 38.05 | 35.23 |
| 3 | 69.67 | 64.65 | 62.94 | 66.09 | 80.00 | 118.28 | 113.16 | 125.76 | 133.03 | 71.62 | 66.32 |
| 4 | 37.01 | 34.35 | 33.44 | 35.11 | 42.50 | 62.83 | 60.12 | 66.81 | 70.67 | 38.05 | 35.23 |
| 5 | 84.50 | 78.41 | 76.34 | 80.16 | 97.03 | 143.46 | 137.25 | 152.54 | 161.35 | 86.86 | 80.43 |
| 6 | 38.10 | 35.36 | 34.42 | 36.14 | 43.75 | 64.68 | 61.89 | 68.78 | 72.75 | 39.17 | 36.27 |
| 8 | 43.00 | 39.90 | 38.85 | 40.79 | 49.38 | 73.00 | 69.84 | 77.62 | 82.10 | 44.20 | 40.93 |
| 9 | 37.01 | 34.35 | 33.44 | 35.11 | 42.50 | 62.83 | 60.12 | 66.81 | 70.67 | 38.05 | 35.23 |
| 10 | 41.36 | 38.39 | 37.37 | 39.24 | 47.50 | 70.23 | 67.19 | 74.67 | 78.98 | 42.52 | 39.38 |
| 11 | 39.97 | 37.09 | 36.11 | 37.91 | 45.90 | 67.85 | 64.92 | 72.15 | 76.32 | 41.09 | 38.05 |
| 12 | 39.73 | 36.87 | 35.90 | 37.69 | 45.63 | 67.45 | 64.54 | 71.73 | 75.87 | 40.84 | 37.82 |
| 13 | 38.10 | 35.36 | 34.42 | 36.14 | 43.75 | 64.68 | 61.89 | 68.78 | 72.75 | 39.17 | 36.27 |
| night | 30.30 | 28.12 | 27.37 | 28.74 | 34.79 | 51.44 | 49.21 | 54.69 | 57.85 | 31.15 | 28.84 |

Next, we will show how to calculate the NOx emissions. Unlike the $CO_2$ emissions, the NOx emissions are not determined by the amount of fuel being consumed. Rather; they are determined by how cleanly the fuel burns; e.g. how correctly the engine has been calibrated to give the right amount of oxygen for the right amount of fuel for the combustion reaction in question. However, this is a difficult thing to quantify without direct measurement. We do note that in previous studies, it has been shown there is a strong correlation between the year that the bus was manufactured and the amount of NOx emissions; because as technology and manufacturing processes improve, so does our ability to improve the quality of the combustion reactions in our busses. Table 3.4 represent the fleet emission of $NO_2$ produced by this study are given here,

Table 3.4: Pollutant emissions by vehicle year

| Pollutant | Calendar Year | Emission Factor (g/mi) | | |
|---|---|---|---|---|
| | | Model Year | Average | 45 MPH |
| ROG | 2013 | Entire Fleet | 0.64 | 0.45 |
| | | 1996-2002 | 0.80 | 0.43 |
| | | 2003-2006 | 0.15 | 0.07 |
| | | 2007-2009 | 0.03 | 0.01 |
| | | 2010-2013 | 0.03 | 0.01 |
| CO | 2013 | Entire Fleet | 2.95 | 3.43 |
| | | 1996-2002 | 1.82 | 1.76 |
| | | 2003-2006 | 1.25 | 0.54 |
| | | 2007-2009 | 1.07 | 0.41 |
| | | 2010-2013 | 1.00 | 0.33 |
| $NO_x$ | 2013 | Entire Fleet | 16.40 | 12.09 |
| | | 1996-2002 | 15.61 | 11.25 |
| | | 2003-2006 | 3.55 | 2.28 |
| | | 2007-2009 | 0.63 | 0.44 |
| | | 2010-2013 | 0.59 | 0.35 |
| PM 2.5-Exhaust | 2013 | Entire Fleet | 0.25 | 0.12 |
| | | 2003-2006 | 0.03 | 0.01 |

Now, it is important to note, that all of the data used in this table are given for Diesel buses, so once again it will be necessary to convert the data of the Gas and Hybrid buses into Diesel-Equivalent gallons using Equations 17 and 18.

Once we've gone through and performed all of these calculations, we obtain the following results for the NOx emissions, collected in Table 3.5 bellow.

Table 3.5: Results of $NO_x$ emissions calculation (kg)

| BN/RN | 91 | 112 | 114 | 113 | 31 | 42 | 976 | 105 | 106 | 103 | 104 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 23.18 | 21.71 | 21.71 | 21.71 | 130.61 | 130.61 | 647.91 | 21.71 | 21.71 | 15.20 | 15.20 |
| 2 | 18.76 | 17.57 | 17.57 | 17.57 | 105.73 | 105.73 | 524.50 | 17.57 | 17.57 | 12.30 | 12.30 |
| 3 | 35.32 | 33.08 | 33.08 | 33.08 | 199.03 | 199.03 | 987.29 | 33.08 | 33.08 | 23.15 | 23.15 |
| 4 | 18.76 | 17.57 | 17.57 | 17.57 | 105.73 | 105.73 | 524.50 | 17.57 | 17.57 | 12.30 | 12.30 |
| 5 | 42.84 | 40.12 | 40.12 | 40.12 | 241.40 | 241.40 | 1197.4 | 40.12 | 40.12 | 28.08 | 28.08 |
| 6 | 19.32 | 18.09 | 18.09 | 18.09 | 108.84 | 108.84 | 539.92 | 18.09 | 18.09 | 12.66 | 12.66 |
| 8 | 21.80 | 20.42 | 20.42 | 20.42 | 122.84 | 122.84 | 609.34 | 20.42 | 20.42 | 14.29 | 14.29 |
| 9 | 18.76 | 17.57 | 17.57 | 17.57 | 105.73 | 105.73 | 524.50 | 17.57 | 17.57 | 12.30 | 12.30 |
| 10 | 20.97 | 19.64 | 19.64 | 19.64 | 118.17 | 118.17 | 586.20 | 19.64 | 19.64 | 13.75 | 13.75 |
| 11 | 20.26 | 18.98 | 18.98 | 18.98 | 114.18 | 114.18 | 566.41 | 18.98 | 18.98 | 13.28 | 13.28 |
| 12 | 20.14 | 18.86 | 18.86 | 18.86 | 113.51 | 113.51 | 563.06 | 18.86 | 18.86 | 13.21 | 13.21 |
| 13 | 19.32 | 18.09 | 18.09 | 18.09 | 108.84 | 108.84 | 539.92 | 18.09 | 18.09 | 12.66 | 12.66 |
| night | 15.36 | 14.39 | 14.39 | 14.39 | 86.56 | 86.56 | 429.37 | 14.39 | 14.39 | 10.07 | 10.07 |

## 3.3 Minimize Cost to Run the Bus

When looking at the cost to run the buses, it is necessary to consider the entire life-cycle of a bus; this is depicted in Figure 3.1.

The following factors all affect the cost of running the bus: Depreciation, fuel cost, insurance, driver cost, repair cost, the number of passengers, estimated years of useful life, and scrap value.

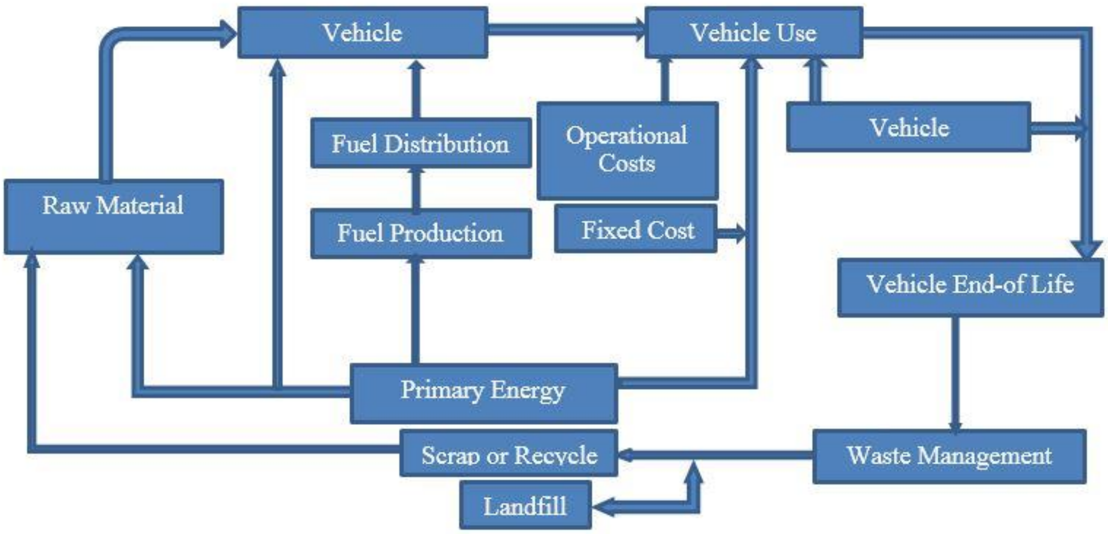


Figure 3.1: life cycle phases of a transit bus [Maclean and Lave 2003]

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**Governing Equation**

$$Total\ Cost\ = \frac{\{[Yearly\ Depreciation]+[Annual\ Fuel\ Cost]+[Annual\ Driver\ Wages]+[Annual\ Cost\ of\ Repairs]\}}{[Annual\ Number\ of\ Passengers]} \quad (24)$$

Where:

$$Yearly\ Depreciation\ = \frac{[Upfront\ Cost\ of\ Purchase] - [Salvage\ Value]}{Expected\ total\ years\ of\ Service} \quad (25)$$

$$Annual\ Fuel\ Cost = [Average\ mpg] \times [Annual\ Miles\ Travelled] \times [Cost\ of\ 1\ Gallon\ of\ Fuel] \quad (26)$$

$$Annual\ Driver\ Wages\ = [Annual\ Service\ hours] \times [Average\ Hourly\ Driver\ Pay\ Rate]$$

(27)

Data and independent cost variable used in these equations are compiled in table 3.5 and table 3.6:

Table 3.5: Independent cost variables

| | |
|---|---|
| Hourly Drivers Wage Rate | $2300 per week |
| Diesel Fuel Prices | $3.825 / Gallon |
| Gasoline Fuel Prices | $3.299 / Gallon |

Where the cost of Diesel and Gasoline fuel are the average cost of each in the 2014 Calendar year across the United States.

Table 3.6: Route-dependent cost variables

| **Route#** | **Annual Service hours** | **Annual Mileage** | **Annual Number of Passengers** |
|---|---|---|---|
| **1** | 3,567.4 | 36,792.0 | 11,100.0 |
| **2** | 3,567.4 | 29,784.0 | 15,452.0 |
| **3** | 3,461.2 | 56,064.0 | 54,656.0 |
| **4** | 3,457.6 | 29,784.0 | 13,844.0 |
| **5** | 3,394.8 | 67,999.5 | 20,660.0 |
| **6** | 3,457.6 | 30,660.0 | 16,776.0 |
| **8** | 3,404.1 | 34,602.0 | 18,684.0 |
| **9** | 3,404.1 | 29,784.0 | 10,496.0 |
| **10** | 3,351.8 | 33,288.0 | 16,412.0 |
| **11** | 3,351.8 | 32,164.0 | 7,256.0 |
| **12** | 3,583.5 | 31,974.0 | 3,140.0 |
| **13** | 3,583.5 | 30,660.0 | 3,684.0 |
| **Night Bus** | 1,241.3 | 24,382.0 | 3,452.0 |

Next, the data for variables dependent on which bus is being driven are listed below in Table 3.7.

Table 3.7: Bus-dependent cost variables

| Bus Type | Salvage Value | Expected years of service | Average mpg | Annual cost of repairs |
|---|---|---|---|---|
| 91 - 25ft gas | $1,000 | 7 | 6.83 | $6,940 |
| 112 - 25 ft gas | $1,000 | 7 | 7.36 | $5,134 |
| 114 - 25 ft gas | $1,000 | 7 | 7.56 | $6,785 |
| 113 - 25 ft gas | $500 | 5 | 7.2 | $3,265 |
| 31- 30 ft. diesel | $5,000 | 12 | 7.2 | $14,782 |
| 42 - 30 ft diesel | $5,000 | 12 | 4.87 | $11,636 |
| 976 - 35 ft diesel | $5,000 | 12 | 5.09 | $8,479 |
| 105- 35 ft. diesel | N/A | 12 | 4.58 | $10,248 |
| 106 - 35 ft. diesel | N/A | 12 | 4.33 | $10,536 |
| 103 - 35 ft. hybrid | N/A | 12 | 5.63 | $8,073 |
| 104 – 35 ft hybrid | N/A | 12 | 6.08 | $10,757 |

## 3.4 Upfront Cost of Purchasing Bus:

The cost to purchase each of the buses currently owned by the city of Grand Forks are given below in Table 3.8 as follows:

Table 3.8: Upfront cost of purchasing buses

| Vehicle Type | Estimated Capital Cost |
|---|---|
| 91 - 25ft gas | $140,000.00 |
| 112 - 25 ft gas | |
| 114 - 25 ft gas | |
| 113 - 25 ft gas | |
| 31- 30 ft. diesel | $350,000.00 |
| 42 - 30 ft diesel | |
| 976 - 35 ft diesel | $460,000.00 |
| 105- 35 ft. diesel | |
| 106 - 35 ft. diesel | |
| 103 - 35 ft. hybrid | $500,000.00 |
| 104 – 35 ft. hybrid | |

## 3.5 Recommended Bus to Purchase

Currently, the city of Grand Forks purchases a new transit bus approximately once every two years. However, the initial cost of purchasing a bus is often one of the most important factors when considering the lifetime cost of the bus to the city, as well as what effect the bus will have on the total carbon footprint of the City of Grand Forks. So, if we can offer input as to which type of busses the city of Grand Forks should purchase in the future, this is likely going to be the simplest and most effective way of improving the overall efficiency of the CAT system.

Unfortunately, this is a very complicated issue with many different facets that must be considered. For example, we might suggest that the city purchases smaller buses that are cheaper and more fuel efficient; since most of the time, the buses operate with under ten passengers at a time, way below their capacity. At a glance, it would not seem that it is necessary for a city as small as Grand Forks to purchase buses that are as large as the buses that we have. However, this is not necessarily the case, because there are perhaps 5 or 6 different events scheduled throughout the year where the buses do operate near capacity; generally during large sporting events or concerts. So, in that light, purchasing smaller busses may not be possible, unless there were more of them.

Another factor that is important to consider when selecting which bus to purchase is the public opinion. We note that many people view taking the bus as a more eco-friendly alternative to driving a car. As such, we might select a Hybrid bus, which the public views as the most eco-friendly alternative. However, as we have discussed elsewhere in this paper, the actual data does not support the popular opinion on this matter; while the hybrid buses do have excellent fuel efficiency, they produce more harmful emissions than diesel or gasoline buses do.

In any case, while there are still many calculations to be done on this project before our results can be considered conclusive in some way, the way it looks right now, we will probably end up suggesting that from now on the city of Grand Forks simply purchase more 25 ft Gasoline buses; as these are the cheapest option by far; you can purchase three of them for the same cost as one hybrid bus, and they also have the lowest operating cost and produce comparatively minimal emissions.

## 3.6 Formulating Preferability Index

The following five variables have been identified as the most important considerations to the city of Grand Forks when selecting which bus should travel on which route. These variables in table 3.9 are also a key parameter for preferability index.

Table 3.9: Applicable factors and their relative importance

| **Factor** | **Importance Weight** | **Ideal Value** |
|---|---|---|
| 1. Fuel Consumption($F_c$) | 10% | 2664.24 Gallons per year |
| 2. CO2 Emissions($E_c$) | 10% | 43,750,117 grams per year |
| 3. NOx Emissions($E_n$) | 10% | 121,766.3 grams per year |
| 4. Cost to Run the bus ($C_r$) | 50% | $0.98 per passenger |
| 5. Upfront cost ($c_p$) | 20% | $140,000.00 |

## 3.7 Preferability Index Equation

To establish which bus is most preferable for which route, it is necessary to combine these four factors into a single index; the "prefer-ability index." This will be accomplished by creating a ratio of the measured value of a certain bus on a certain route to the idealized value we would hope to achieve, then multiplying that value by the importance weight of the factor, and finally adding those values for all four factors together.

$$Preferability\ index\ =\ Fc(.1) + Ec(.1) + En(.1) +\ Cr(.5) +\ Cp(.2) \qquad (28)$$

Table: 3.10 Annual fuel cost comparison between existing and proposed bus

| Route | Annual Mileage | Bus assignment | | Fuel Requirement | | Annual Cost | |
|---|---|---|---|---|---|---|---|
| | | Current | Proposed | Current | Proposed | Current | Proposed |
| Route 1/2 | 55,996.80 | 95,112 | 114 | 7,892.43 | 7,406.98 | $13,409.24 | $12,584.47 |
| Route 5 | 55,950.75 | 105,106 | 112 | 12,573.20 | 7,602.00 | $25,385.30 | $12,915.80 |
| Route 10/11 | 54,369.70 | 114 | 113 | 7,191.76 | 7,551.35 | $12,218.80 | $12,829.74 |
| Route 10/11 | 52,681.20 | 113 | 91 | 7,316.83 | 7,713.21 | $12,431.30 | $13,104.74 |
| Route 10/11 | 51,898.35 | 31,42 | 104 | 8,599.56 | 8,535.91 | $17,362.51 | $17,234.01 |
| Route 10/11 | 50,839.20 | 103 | 103 | 9,030.05 | 9,030.05 | $18,231.68 | $18,231.68 |
| Route 10/11 | 46,172.80 | 104 | 31 | 7,594.21 | 6,412.89 | $15,332.71 | $12,947.62 |
| Route 10/11 | 20,507.60 | 976 | 105 | 4,029.00 | 4,477.64 | $8,134.55 | $9,040.36 |
| Total | | | | | | $122,506.08 | $108,888.41 |

Depending on the five variables, we created charts for each and extracted value to use as a desirable index. For example, the upfront cost of purchasing a 25 feet gasoline bus would be $14,000 which is the lowest of the other available option. Finally, we created table according to highest to lowest preferability index for all the 13 route. Moreover, the route that is coupled together is considered as one after averaging and routes with longest operation distance were given most priority when assigned with the highest fuel efficient bus.

Based on Cities Area Transit current buses assignment, the total annual fuel cost is $122,506.08.

The analytical calculation results on annual fuel cost are summarized in Table 3.10, which is based on proposed optimal bus assignment model. Comparing results in Table 3.10, using our proposed bus assignment model, the right bus our projected model delivered almost similar sets of bus assignment for the individual route. After the reassignment of the bus, we get $13,617.67 savings per year with the current fuel cost.

### 3.8 Emission Reduction

With the updated bus assignment, the overall $CO_2$ emission was reduced more than 12 percent. 2.68 Kg of $CO_2$ is produced for 1 liter of diesel and 2.31 Kg of $CO_2$ is produced from each liter of gasoline.

We calculated $CO_2$ emission for both the assignment and there was a significant amount of $CO_2$ reduction was observed due to fact that, route 5; being the longest route among all the routes and was operated with the oldest bus of the fleet. Replacing the oldest 35- feet diesel bus with a 25 feet gasoline bus was the effective solution for reducing $CO_2$ emission presented in figure 3.2.

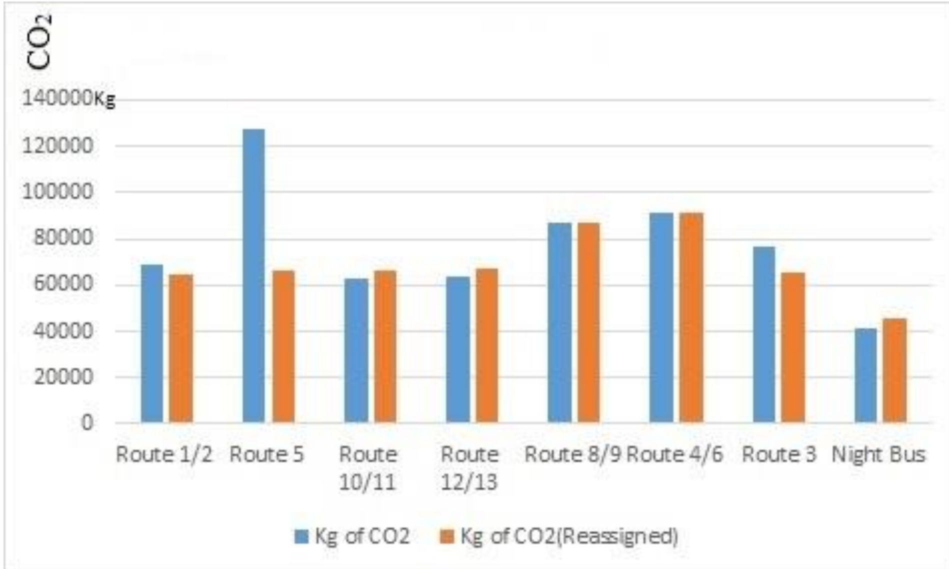



Figure 3.2 $CO_2$ emission comparison

# CHAPTER 4

# ESTIMATION OF FUEL ECONOMY, EMISSION AND LIFE CYCLE COST BASED ON IBIS DATABASE

The selection process and procurement of right transit bus with fuel and powertrain technology is vital for any cost-effective transportation service. There are cities in which conventional diesel-fueled bus is used for transit service. It is not always viable to replace the whole or part of the fleet with the vehicle with a different powertrain. Every city is unique in its road type, road grade, routes, meteorological aspects and traffic population. Since each of the powertrain technology offers a different combination of advantages and disadvantages, we need to study and analysis each one of them individually to find out the best match for our city. There is a variation in transit bus types that are suitable for different kinds of cities, services, and operations. Fuel economy is directly related to the bus size, engine technology, and powertrain. Evaluating fuel economy correctly, predicting detailed emission for the greenhouse gasses and analyzing life cycle cost could be a daunting task and often needs expensive onboard equipment and intricate simulation testing. Lacking this kind of amenities makes it impossible for transit service to conduct research on a county scale and project level. In this study, a local database of transit service was generated from a well-documented database to provide a detailed analysis of fuel economy and emission. The integral part of evaluating fuel economy was compared with test data over the proper drive cycle. This research the standard drive cycles are discussed, and relevant drive cycles are selected for public city transit network. Selecting appropriate drive cycle from the available database requires rigorous examination and experience. The methodology adopted to validate the selection is discussed in details in this study. Selected drive cycles are also used to analyze the life cycle costing for different powertrains. Comparative advantages and disadvantages are presented, and best mode of transit is recommended with proper justification using the database. While the fuel economy and emission information could be used to compare with the EPA regulated values and life-cycle costing can be derived from the Department of Transportation, combining these two factors, a precise local database of transit fleet can be constructed for any size of city transit authority

## 4.1 Background

The diesel engine is identified as the primary source for both NOx and particulate matter. Environmental Protection Agency (EPA) also reported diesel as a "potential occupational carcinogen" [30]. However, it is not always viable to replace the whole or part of the fleet with a vehicle with a different powertrain. Every city is unique in its road type, road grade, routes, meteorological aspects and traffic population. Since each of the powertrain technology offers a different combination of advantages and disadvantages, we need to study and analysis each drivetrain technology to find out the best match for our city.

In the upcoming years, hybrid bus held the key to fuel consumption reduction and supposed to be the primary choice for transit service providers since it appears to be the cheapest options regarding total cost of ownership [31]. First of all, hybrid electric bus regenerates and reuse the energy because it operates on a stop and go pattern. Secondly, hybrid bus helps to reduce the engine size, idle engine stop and reducing transient engine operation. However, hybrid-bus has high capital cost and the way down on its sixth or seventh year of operation; the battery needs to be replaced with years of capacity loss [32].

On the other hand, CNG buses have gained popularity recently due to the fact that its popular perception of less greenhouse gas emission. Compared to conventional gasoline and diesel-fueled bus, CNG buses emits very low amount of particulate matter (PM). Moreover, relatively low fuel price and improved fuel conservation strategy have made CNG buses more attractive and environment-friendly [33]. The problem associated with operating CNG buses are high initial installation cost of refueling station and excessive vehicle weight from onboard storage tanks.

Finally, the conventional diesel-fueled buses remain leading technology in transit business since it offers the lowest capital cost and relatively less maintenance cost. Non-hybrid diesel buses remain the most fuel-efficient vehicle due to its high power density. However, diesel engine manufacturer has to equip the buses with diesel particulate filter combined with catalytic reduction technologies to keep up with the Environmental Potential Agency (EPA) guidelines [34].Considering all the facts above, we can see that finding the right mode of transit bus for a city is not a straightforward decision to make. There has to be some trade-off between economic and environmental requirements.

Transit related research with a goal to find out the fuel consumption and emission is primarily done with the aid of on-board device integrated with high-end computing technologies. There is a variety of gas analyzer retrofitted with the emission to collect the information regarding fuel economy and emission which monitor and record second by second data [35]. The study of comparative drivetrain analysis has been done on some simulation platform. In recent years Autonomie from Argonne National Laboratory of quite capable of vehicle level control technologies validation and lifecycle analysis [36] [37] [38]. Another Matlab/Simulink based simulation program for rapid analysis of the performance and fuel economy of light and heavy-duty vehicle with conventional, hybrid electric, full-electric and fuel cell powertrain [39][40].

In the field of academic research, Motor Vehicle Emission Simulator (MOVES) is used widely in the US on a county, national and project level analysis. Jinghui Wang, Hesham A. Rakha has described briefly about it in [41]. A novel approach for fuel consumption modeling is MOVES integrated with Physical Emission Rate Simulator (PERE) which complements the MOVES by calculating fuel rates by vehicle specific power, engine mass, and vehicle speed. The biggest limitation of MOVES database is it does not includes the most accurate up to date information at local level analysis, and it also uses default driving behavior and road type distribution. Moreover, detailed data is almost impossible to acquire for project level analysis which makes the geographic bound inaccurate. For transit level analysis and vehicle procurement analysis it is very difficult to create local database using project-level analysis because providing information on vehicle age distribution, vehicle average speed distribution, vehicle miles traveled, and meteorologist data in the form of user specified data.

Although on-road vehicle performance diverges from the regulatory test, drive cycle testing has always been the primary laboratory testing. It's always a better practice to get the emission data using Portable Emission Measurement Systems (PEMS).However, not every transit agency has these expensive tools and intricate data analysis expertise for research and formulate policies accordingly. Hence the necessity arises for the use of drive cycle to determine the fuel consumption and emission of Green House Gases (GHG).

A driving cycle often refers to as vehicle profile is the mathematical representation of vehicle speed versus time. Different vehicle manufacturer follows different drive cycle for laboratory testing. However, not a single standard drive cycle can represent the accurate driving behavior or real world driving pattern. Zaccardi and Le Berr showed in their research how different drive cycle could be combined to represent real world driving [38]. However, it is not advisable to compare two different drive cycle result because two different drive cycle has different vehicle excitation.

To avoid these intricacies and make budget and procurement easier for transit agencies, a local database is created using West Virginia University generated Integrated Bus Information System (IBIS). IBIS has developed a set of convenient tool for evaluating the pollutant emission, greenhouse gasses, and fuel economy of transit buses. It contains both searchable database of transit vehicle emission test data and a transit fleet emissions fleet emission inventory.

## 4.2 Transit Bus Fuel Consumption Database

A transit bus stops at a different location including the designated stops on a route like the traffic signals and the stops sign. To calculate the real number of stops per mile, we have to consider all of these stops together. The average speed was coupled with some stops per mile to screen out the eligible drive cycles which reflect the best pattern with the routes here in the city. To generate the local database, the most important step is to collect information regarding driving routes and identify the best match from the standard driving cycle. For this, three parameters are required such as service hours, stops per mile and a total number of stops. Both geographic information system (GIS) and Google street view were employed to find out the total number of stops. Designated stops were extracted from the GIS bus routes. Additional stop road sign was determined using google street view. These additional number of stops were added to find out the total number of stops. Therefore, dividing total stops by individual miles of the routes stops per mile is determined. The average speed of all the routes was found by dividing miles of the routes by corresponding service hour. Finally, all the calculation is merged into a combined route calculation. The conjugal routes were coupled together.

After the combined calculation of the routes, appropriate drive cycle needs to be selected. In this stage, the process of elimination is followed to narrow down the choices from 22 available standard drive cycle. Given the size of the city and the nature of the urban driving cycle, the average speed for any combined route varies from 25 to 30 mph. So any standard cycle with a maximum speed of above 40 mph with a lower number of stops per mile was taken out of consideration. After a rigorous examination of the standard cycles, only four of the cycles were chosen from the available selection. These four cycles are Central Business District cycle (figure 6), Orange County Transit Authority Bus Cycle, New York Composite Cycle and Route 22.

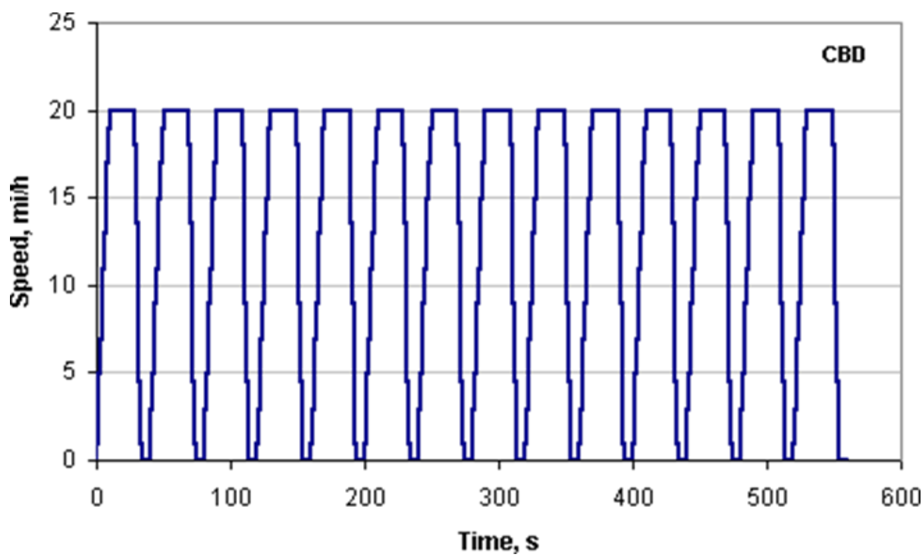



Figure 4.1. Central business district cycle. West Virginia University brochure.

## 4.3 Transit Fleet Modeling Methodology

To model a fleet in IBIS, the user defines a set of "virtual buses." Each virtual bus represents the characteristics of an actual vehicle in the existing fleet or a vehicle that is being considered for purchase. The characteristics defined for each virtual vehicle include vehicle parameters and driving characteristics. The vehicle parameters include technical characteristics of the vehicle such as the type of fuel, powertrain type (conventional or hybrid), length, model year, curb weight, occupancy, engine rated power, after-treatment equipment, displacement, the number of cylinders, transmission type, type of heating system, and capacity of air conditioning. The driving characteristics describe the manner in which the vehicle is driven in service and include the average speed with idle, the number of starts/ stops per mile, percentage idle, and standard deviation of speed with idle, and kinetic intensity. A fleet is then comprised by specifying the number of each virtual vehicle.

Table 4.1: Estimated CAT fleet from database

| Bus No | Model Year | Fuel and Drivetrain | Average Annual Miles | Driving Cycle | MPG | NOx (g/mi) | PM (g/mi) | HC (g/mi) | CO (g/mi) | CO2 (g/mi) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2009 | Gasoline | 21,510 | OCTABC | 3.700 | N/A | 0.030 | 0.318 | 16.532 | 2,370.7 |
| 2 | 2011 | Gasoline | 41,317 | OCTABC | 3.400 | 1.206 | 0.027 | 0.369 | 21.483 | 2,573.9 |
| 3 | 2011 | Gasoline | 44,011 | OCTABC | 3.500 | N/A | 0.028 | 0.488 | 18.497 | 2,513.3 |
| 4 | 2011 | Gasoline | 48,582 | OCTABC | 3.400 | 0.227 | 0.030 | 0.438 | 19.431 | 2,574.7 |
| 5 | 2003 | Diesel | 31,519 | CBD | 4.126 | 8.838 | 0.180 | 0.785 | 2.653 | 2,307.8 |
| 6 | 2004 | Diesel | 29,681 | OCTABC | 4.051 | 8.840 | 0.152 | 0.820 | 2.882 | 2,326.5 |
| 7 | 1997 | Diesel | 23,254 | Braunschweig Cycle | 4.171 | 26.561 | 0.250 | 0.134 | 3.421 | 2,405.0 |
| 8 | 2010 | Diesel | 37,376 | CBD | 4.126 | 8.838 | 0.180 | 0.785 | 2.653 | 2,307.8 |
| 9 | 2010 | Diesel | 47,707 | CBD | 4.126 | 8.838 | 0.180 | 0.785 | 2.653 | 2,307.8 |
| 10 | 2010 | Hybrid | 40,254 | CBD | 4.714 | 8.467 | 0.015 | 0.024 | 0.027 | 1,948.5 |
| 11 | 2010 | Hybrid | 37,226 | CBD | 4.714 | 8.467 | 0.015 | 0.024 | 0.027 | 1,948.5 |

The fuel consumption and emission database of table 15 was created maintaining some uniformity for accuracy. Model year and appropriate engine technology were chosen for the diesel and diesel-electric buses. Some of the gasoline buses of CAT were not included in the IBIS WVU. Only one New Flyer model on Orange County Transit Authority Bus Cycle (OCTABC) was tested in the facilities. Hence for convenience, all four gasoline buses were replaced with the data and accounted for fuel consumption and emission.

### 4.4 Bus Life Cycle Cost Model

A life cycle costing model is developed using the IBIS WVU database and compared to budget and procurement analysis. Four different powertrain bus technologies were analyzed in WVU facility, and the report was published with associated cost and performance data including the emission measurement from existing WVU database. The all-inclusive report was based on 100 bus purchase in 2007 and assumed an operating bus life cycle of 12 years. The information presented in the report was based on both capital and operating cost. Maintenance and infrastructural cost, battery replacement, refueling station and propulsion system maintenance cost were also included in the overall cost.

The IBIS is an accessible online tool that can be used to estimate the existing transit fleet fuel economy and emission and also the changes associated with the integration of new bus to the overall system. It is always preferable to carry out transit-related research with onboard equipment like gas analyzer and GPS; however, it is not always possible for transit authorities to have enough resources or workforce to go through the process. In this kind of situation, this online tool has the potential to determine the fuel consumption over specified drive cycle and forecast the emission of greenhouse gasses and particulate matter.

Both the fuel consumption model and the preferability-index model confirms that the 1997 model 30 feet diesel bus were the one responsible for the highest fuel consumption and excessive NOx emission in the atmosphere. So an analysis was carried out to find out the best match for the city of Grand Forks from the available technology which would result in higher fuel economy and lesser emission. In WVU database, there are only four different technology buses are available to compare side by side. However, we will not include the CNG powered bus since; apart from the capital cost, there is an additional cost for equipment and training cost. It also requires specialized fueling, maintenance, and storage infrastructure.

First of all, we set the purchase year within the fiscal year 2016 for all the option we considered. Then we change the annual mileage of the bus to 23254 miles from the CAT database associated with the 30 feet diesel bus mileage. For all the bus technologies we selected tax rate for North Dakota. The LCC tools assume the fuel economy from the WVU database where 100 buses were tested over selected drive cycle. All the buses were assumed to be of service for a lifetime of twelve years. It was also assumed that the engine was checked and rehabilitated after every seven years if necessary. When specifying the scenario, we also select four important parameters which are annual mileage, average speed, air conditioning and gas heater. Considering the number of stops and stops per mile, we set the average speed to be 20 miles per hour. Statistically, Grand Forks has been a city with long and harsh winter. So, for air-conditioning on a sale from 0 to 10 we selected 4, and on the same scale, we selected gas heater to be used as nine throughout the year.

Three different scenario were created in table 16 and compared side by side for evaluation purpose. In the first scenario, we selected conventional diesel bus with a one-time capital cost of $369400. Unlike a diesel-electric and gasoline-electric bus, conventional diesel buses don’t require training for the maintenance and battery replacements. With relatively lower fuel economy of 3.78 miles per gallon, the overall fuel consumption per gallon is accrued to 6151 gallons per year. For a total lifespan of 12 years including an engine replacement at seventh year, the total cost for operating conventional diesel bus is $826,200.

Table 4.2: Comparative life cycle costing

| Technology | Conventional Diesel | Diesel-Electric Hybrid | Gasoline Electric Hybrid |
|---|---|---|---|
| **Quantity** | 1 | 1 | 1 |
| **Purchase Year** | 2016 | 2016 | 2016 |
| **Annual Mileage Per Bus** | 23,254 | 23,254 | 23,254 |
| **Training Costs** | N/A | $1,295 | $1,295 |
| **Purchase Cost per Bus** | $396,400 | $436,600 | $428,800 |
| **Purchase Cost per Bus after Credits** | $396,400 | $436,600 | $428,800 |
| **Engine Replacement Cost per Bus** | $20,650 | $20,650 | $20,650 |
| **Transmission Replacement Cost per Bus** | $16,170 | $49,340 | $49,340 |
| **Energy Storage Replacement Cost per Bus** | 0 | $60,120 | $60,120 |
| **Unscheduled Maintenance per Mile** | $0.39 | $0.43 | $0.43 |
| **Scheduled Maintenance per Mile** | $0.22 | $0.19 | $0.19 |
| **Fuel Economy (MPG)** | 3.78 | 4.3 | 3.92 |
| **Fuel Consumption per Year per Bus** | 6,151 | 5,407 | 5,932 |
| **Fuel Cost per Gallon including Taxes** | $3.02 | $3.02 | $2.80 |
| **Fuel Cost per Gallon including Taxes and Credits** | $3.02 | $3.02 | $2.80 |

| | | | |
|---|---|---|---|
| **Vehicle Capital** | $433,200 | $566,700 | $558,900 |
| **Other Capital** | $0.00 | $1,295 | $1,295 |
| **Unscheduled Costs** | $108,800 | $120,000 | $120,000 |
| **Scheduled Costs** | $61,390 | $53,020 | $53,020 |
| **Total Fuel Costs** | $222,800 | $195,800 | $199,200 |
| **Total Capital Costs** | $433,200 | $568,000 | $560,200 |
| **Total Variable Costs** | $393,000 | $368,800 | $372,200 |
| **Total** | $826,200 | $936,800 | $932,400 |

The additional cost associated with the hybrid bus is training costs and energy storage replacement after the life cycle of the batteries. So the final overall cost for the diesel-electric and gasoline-electric bus is respectively $936,800 and $932,400. Figure 4.2 represent the cost breakdown importance factor graphically.  Therefore, we can conclude conventional diesel powertrain is the best option for Grand Forks Transit authority.

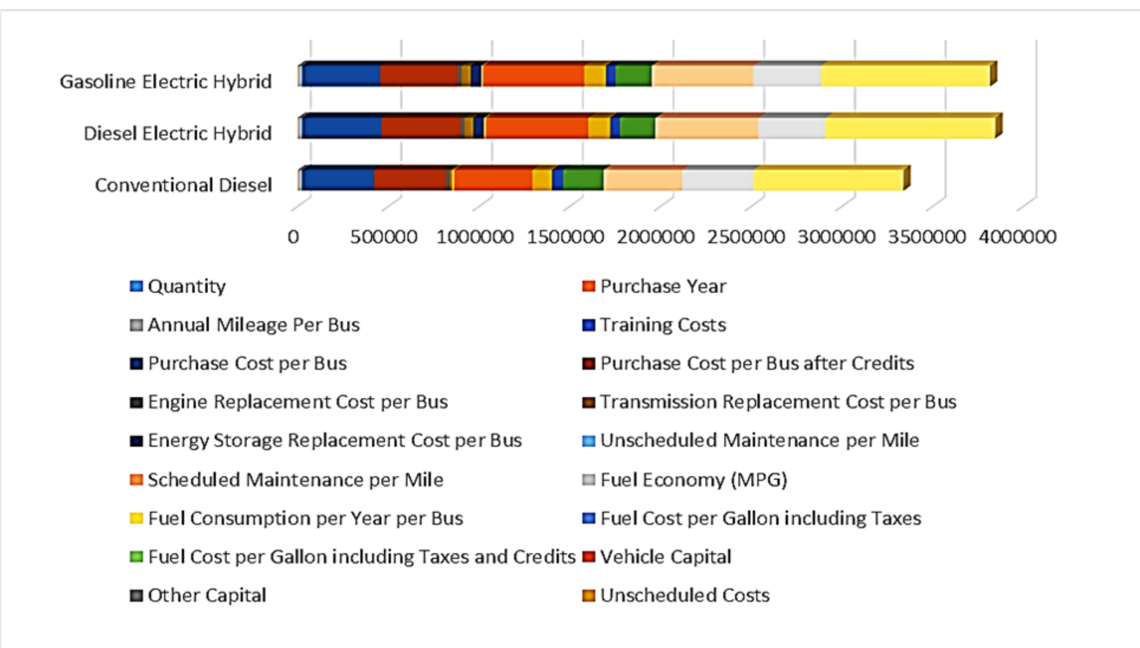



Figure 4.2: Comparative life cycle costing

In this research, a local database of fuel economy and emission is estimated from a reliable database of IBIS with a separate database of life cycle costing. Appropriate drive cycle was selected for each route for fuel consumption calculation and emission estimation. The fuel economy estimation would help the transit agency to find out the best combination of the bus in the fleet for optimal performance. The life cycle costing analysis would provide deeper insight into the decision making of bus procurement and budget finalizing.

# CHAPTER 5

## CONCLUSION & FUTURE WORK

### 5.1 Conclusion

The purpose of this study was to provide necessary data backed up by engineering research to the City of Grand Forks. This study is essential to estimate fuel consumption and emission without the aid of traditional expensive onboard devices. Bus model and year play a huge impact on the fuel consumption which directly effects on the operating cost of the transit agency. Transit service with appropriate bus fleet is necessary for the sound operation in a small city like Grand Forks. It is a well-known trait in transit service; when operated with relatively old bus fleet, faces increased cost for operating and maintenance. The objective of this research is to generate an optimization plan from the existing resource of local transit service having gasoline, diesel and hybrid-electric vehicles of a different type. Using the real world data with measured analytical data a mathematical model is developed and verified.

Fleet data analysis and studies have shown that per-mile operation and maintenance cost increase with the operating bus age. Managing and financing the operation in an optimal manner is essential to every transit agencies. The Higher rate of emission at the edge of the life cycle buses is also a concern since EPA (Environment Protection Agency) has rules and protocol for a city and fleet data emission. From an economic perspective, the upfront capital cost to replace older buses with the newer one is high even taking subsidy into account. So there has to be a balance between the timing of purchase and replacement magnitude. This important issue of budget and procurement was also included in the study

This study demonstrated a fleet optimization model that minimize fuel consumption over specific routes and also minimize $CO_2$ emission. This model can apply to any size of fleet transit for evaluation and optimization including different types of vehicle. This model complements the previously generated fuel consumption model. This model could be extensively used for transit fleet which does not have real-world operational data.

This model considers the constraint set by the transit agency as well as it recommends the best type of bus to purchase for the future. Therefore, any transit agency could use this model during budget and procurement. This also allows to find out and eliminate the less fuel efficient vehicle of the fleet and replace with a new one. Both fuel consumption model and the preferability index model complement each other. Since the later could be used to validate the former, the both could be used in conjunction for bus to route assignment or resource optimization. The preferability model has the potential to include more than five variables.

## 5.2 Future Work

There is an ample opportunity to further develop this model by analyzing and simulating in project level. There is also an opportunity to make the model adaptable to changing weather. The mathematical model includes the drag coefficient and frontal area of the bus. Both of these variable plays a significant role in fuel consumption. Therefore, the model has the potential to be more accurate if the value of these two variable could be obtained through ANSYS Fluent.

Life cycle costing preparation from the database is not always the best practice for transit agencies. Due to distinctive nature of the standard drive cycle and the vehicle tested over the cycle vary a lot regarding speed and driving characteristics from city to city. The database considers the fuel price to be constant for the fuel consumption calculation; however, in real life, the fuel cost fluctuate a great deal over 12 years period. Moreover, the infrastructural cost, scheduled and unscheduled cost also vary over the years. For emission prediction, the fuel economy of the local transit fleet was not always close to database. As a result the closest match was needed to assume. At this moment, the standard drive cycle for each route is selected based upon experience and calculation. However, there is a huge scope for implementing unsupervised machine learning algorithm to select best possible cycle from the available ones.

## 5.3 My Contribution

My contribution to this research was to develop analytical model for calculating fuel consumption and emission estimation. The model developed can be implemented by any transportation agency Moreover, the methodology adopted to generate local database of fuel economy and emission complies with both EPA and TRB. I have also provided a Graphical User Interface to CAT for analyze and compare the model developed in the study. As the result of research conducted in this thesis, the following journal and conference paper were written:

1. E Rabbi, Yang, "Fuel Consumption Model for Optimal Transit Buses Assignment of Gasoline, Diesel and Hybrid Diesel -Electric Buses to Service Route." CSME 2016.
2. E Rabbi, Yang, "Estimation of Fuel Economy, Emission and Life Cycle Cost Based on IBIS Database" [ASME IMECE-2017].

**APPENDICES**

# APPENDIX A

Tables from preferability index model

Annual fuel consumption (gallons)

| BN/RN | 91 | 112 | 114 | 113 | 31 | 42 | 976 | 105 | 106 | 103 | 104 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 5,386.8 | 4,998.9 | 4,866.7 | 5,110.0 | 5,110.0 | 7,554.8 | 7,228.3 | 8,033.2 | 8,497.0 | 6,535.0 | 6,051.3 |
| **2** | 4,360.8 | 4,046.7 | 3,939.7 | 4,136.7 | 4,136.7 | 6,115.8 | 5,851.5 | 6,503.1 | 6,878.5 | 5,290.2 | 4,898.7 |
| **3** | 8,208.5 | 7,617.4 | 7,415.9 | 7,786.7 | 7,786.7 | 11,512.1 | 11,014.5 | 12,241.0 | 12,947.8 | 9,958.1 | 9,221.1 |
| **4** | 4,360.8 | 4,046.7 | 3,939.7 | 4,136.7 | 4,136.7 | 6,115.8 | 5,851.5 | 6,503.1 | 6,878.5 | 5,290.2 | 4,898.7 |
| **5** | 9,956.0 | 9,239.1 | 8,994.6 | 9,444.4 | 9,444.4 | 13,962.9 | 13,359.4 | 14,847.1 | 15,704.3 | 12,078.1 | 11,184.1 |
| **6** | 4,489.0 | 4,165.8 | 4,055.6 | 4,258.3 | 4,258.3 | 6,295.7 | 6,023.6 | 6,694.3 | 7,080.8 | 5,445.8 | 5,042.8 |
| **8** | 5,066.2 | 4,701.4 | 4,577.0 | 4,805.8 | 4,805.8 | 7,105.1 | 6,798.0 | 7,555.0 | 7,991.2 | 6,146.0 | 5,691.1 |
| **9** | 4,360.8 | 4,046.7 | 3,939.7 | 4,136.7 | 4,136.7 | 6,115.8 | 5,851.5 | 6,503.1 | 6,878.5 | 5,290.2 | 4,898.7 |
| **10** | 4,873.8 | 4,522.8 | 4,403.2 | 4,623.3 | 4,623.3 | 6,835.3 | 6,539.9 | 7,268.1 | 7,687.8 | 5,912.6 | 5,475.0 |
| **11** | 4,709.2 | 4,370.1 | 4,254.5 | 4,467.2 | 4,467.2 | 6,604.5 | 6,319.1 | 7,022.7 | 7,428.2 | 5,713.0 | 5,290.1 |
| **12** | 4,681.4 | 4,344.3 | 4,229.4 | 4,440.8 | 4,440.8 | 6,565.5 | 6,281.7 | 6,981.2 | 7,384.3 | 5,679.2 | 5,258.9 |
| **13** | 4,489.0 | 4,165.8 | 4,055.6 | 4,258.3 | 4,258.3 | 6,295.7 | 6,023.6 | 6,694.3 | 7,080.8 | 5,445.8 | 5,042.8 |
| **night** | 3,569.8 | 3,312.8 | 3,225.1 | 3,386.4 | 3,386.4 | 5,006.6 | 4,790.2 | 5,323.6 | 5,630.9 | 4,330.7 | 4,010.2 |

Annual fuel consumption (diesel equivalent gallons)

| BN/RN | 91 | 112 | 114 | 113 | 31 | 42 | 976 | 105 | 106 | 103 | 104 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 4,450.0 | 4,129.5 | 4,020.3 | 4,221.3 | 5,110.0 | 7,554.8 | 7,228.3 | 8,033.2 | 8,497.0 | 6,535.0 | 6,051.3 |
| **2** | 3,602.4 | 3,343.0 | 3,254.5 | 3,417.2 | 4,136.7 | 6,115.8 | 5,851.5 | 6,503.1 | 6,878.5 | 5,290.2 | 4,898.7 |
| **3** | 6,780.9 | 6,292.6 | 6,126.2 | 6,432.5 | 7,786.7 | 11,512.1 | 11,014.5 | 12,241.0 | 12,947.8 | 9,958.1 | 9,221.1 |
| **4** | 3,602.4 | 3,343.0 | 3,254.5 | 3,417.2 | 4,136.7 | 6,115.8 | 5,851.5 | 6,503.1 | 6,878.5 | 5,290.2 | 4,898.7 |
| **5** | 8,224.5 | 7,632.3 | 7,430.4 | 7,801.9 | 9,444.4 | 13,962.9 | 13,359.4 | 14,847.1 | 15,704.3 | 12,078.1 | 11,184.1 |
| **6** | 3,708.3 | 3,441.3 | 3,350.2 | 3,517.8 | 4,258.3 | 6,295.7 | 6,023.6 | 6,694.3 | 7,080.8 | 5,445.8 | 5,042.8 |
| **8** | 4,185.1 | 3,883.7 | 3,781.0 | 3,970.0 | 4,805.8 | 7,105.1 | 6,798.0 | 7,555.0 | 7,991.2 | 6,146.0 | 5,691.1 |
| **9** | 3,602.4 | 3,343.0 | 3,254.5 | 3,417.2 | 4,136.7 | 6,115.8 | 5,851.5 | 6,503.1 | 6,878.5 | 5,290.2 | 4,898.7 |
| **10** | 4,026.2 | 3,736.2 | 3,637.4 | 3,819.3 | 4,623.3 | 6,835.3 | 6,539.9 | 7,268.1 | 7,687.8 | 5,912.6 | 5,475.0 |
| **11** | 3,890.2 | 3,610.1 | 3,514.6 | 3,690.3 | 4,467.2 | 6,604.5 | 6,319.1 | 7,022.7 | 7,428.2 | 5,713.0 | 5,290.1 |
| **12** | 3,867.2 | 3,588.8 | 3,493.8 | 3,668.5 | 4,440.8 | 6,565.5 | 6,281.7 | 6,981.2 | 7,384.3 | 5,679.2 | 5,258.9 |
| **13** | 3,708.3 | 3,441.3 | 3,350.2 | 3,517.8 | 4,258.3 | 6,295.7 | 6,023.6 | 6,694.3 | 7,080.8 | 5,445.8 | 5,042.8 |
| **night** | 2,949.0 | 2,736.6 | 2,664.2 | 2,797.5 | 3,386.4 | 5,006.6 | 4,790.2 | 5,323.6 | 5,630.9 | 4,330.7 | 4,010.2 |

Annual $CO_2$ emissions (Kg)

| BN/RN | 91 | 112 | 114 | 113 | 31 | 42 | 976 | 105 | 106 | 103 | 104 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 45,719.1 | 42,426.9 | 41,304.5 | 43,369.7 | 52,500.1 | 77,618.3 | 74,263.5 | 82,533.0 | 87,298.2 | 46,998.3 | 43,519.9 |
| **2** | 37,010.7 | 34,345.6 | 33,436.9 | 35,108.8 | 42,500.1 | 62,833.8 | 60,118.0 | 66,812.4 | 70,669.9 | 38,046.3 | 35,230.4 |
| **3** | 69,667.3 | 64,650.5 | 62,940.1 | 66,087.1 | 80,000.2 | 118,275.5 | 113,163.4 | 125,764.5 | 133,025.8 | 71,616.5 | 66,316.0 |
| **4** | 37,010.7 | 34,345.6 | 33,436.9 | 35,108.8 | 42,500.1 | 62,833.8 | 60,118.0 | 66,812.4 | 70,669.9 | 38,046.3 | 35,230.4 |
| **5** | 84,498.8 | 78,413.9 | 76,339.5 | 80,156.5 | 97,031.5 | 143,455.2 | 137,254.8 | 152,538.6 | 161,345.7 | 86,863.0 | 80,434.0 |
| **6** | 38,099.3 | 35,355.7 | 34,420.4 | 36,141.4 | 43,750.1 | 64,681.9 | 61,886.2 | 68,777.5 | 72,748.5 | 39,165.3 | 36,266.5 |
| **8** | 42,997.8 | 39,901.5 | 38,845.9 | 40,788.2 | 49,375.1 | 72,998.1 | 69,843.0 | 77,620.3 | 82,101.8 | 44,200.8 | 40,929.4 |
| **9** | 37,010.7 | 34,345.6 | 33,436.9 | 35,108.8 | 42,500.1 | 62,833.8 | 60,118.0 | 66,812.4 | 70,669.9 | 38,046.3 | 35,230.4 |
| **10** | 41,364.9 | 38,386.2 | 37,370.7 | 39,239.2 | 47,500.1 | 70,226.1 | 67,190.7 | 74,672.7 | 78,984.0 | 42,522.3 | 39,375.1 |
| **11** | 39,968.2 | 37,090.1 | 36,108.8 | 37,914.3 | 45,896.2 | 67,854.8 | 64,922.0 | 72,151.3 | 76,317.1 | 41,086.5 | 38,045.6 |
| **12** | 39,732.1 | 36,871.0 | 35,895.5 | 37,690.3 | 45,625.1 | 67,454.0 | 64,538.5 | 71,725.1 | 75,866.3 | 40,843.8 | 37,820.8 |
| **13** | 38,099.3 | 35,355.7 | 34,420.4 | 36,141.4 | 43,750.1 | 64,681.9 | 61,886.2 | 68,777.5 | 72,748.5 | 39,165.3 | 36,266.5 |
| **night** | 30,298.0 | 28,116.2 | 27,372.4 | 28,741.0 | 34,791.8 | 51,437.5 | 49,214.3 | 54,694.5 | 57,852.3 | 31,145.7 | 28,840.5 |

Annual NOx emissions (Kg)

| BN/RN | 91 | 112 | 114 | 113 | 31 | 42 | 976 | 105 | 106 | 103 | 104 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 23,179.0 | 21,707.3 | 21,707.3 | 21,707.3 | 130,611.6 | 130,611.6 | 647,907.1 | 21,707.3 | 21,707.3 | 15,195.1 | 15,195.1 |
| 2 | 18,763.9 | 17,572.6 | 17,572.6 | 17,572.6 | 105,733.2 | 105,733.2 | 524,496.2 | 17,572.6 | 17,572.6 | 12,300.8 | 12,300.8 |
| 3 | 35,320.3 | 33,077.8 | 33,077.8 | 33,077.8 | 199,027.2 | 199,027.2 | 987,287.0 | 33,077.8 | 33,077.8 | 23,154.4 | 23,154.4 |
| 4 | 18,763.9 | 17,572.6 | 17,572.6 | 17,572.6 | 105,733.2 | 105,733.2 | 524,496.2 | 17,572.6 | 17,572.6 | 12,300.8 | 12,300.8 |
| 5 | 42,839.7 | 40,119.7 | 40,119.7 | 40,119.7 | 241,398.2 | 241,398.2 | 1,197,471.0 | 40,119.7 | 40,119.7 | 28,083.8 | 28,083.8 |
| 6 | 19,315.8 | 18,089.4 | 18,089.4 | 18,089.4 | 108,843.0 | 108,843.0 | 539,922.6 | 18,089.4 | 18,089.4 | 12,662.6 | 12,662.6 |
| 8 | 21,799.3 | 20,415.2 | 20,415.2 | 20,415.2 | 122,837.1 | 122,837.1 | 609,341.2 | 20,415.2 | 20,415.2 | 14,290.6 | 14,290.6 |
| 9 | 18,763.9 | 17,572.6 | 17,572.6 | 17,572.6 | 105,733.2 | 105,733.2 | 524,496.2 | 17,572.6 | 17,572.6 | 12,300.8 | 12,300.8 |
| 10 | 20,971.4 | 19,639.9 | 19,639.9 | 19,639.9 | 118,172.4 | 118,172.4 | 586,201.7 | 19,639.9 | 19,639.9 | 13,747.9 | 13,747.9 |
| 11 | 20,263.3 | 18,976.8 | 18,976.8 | 18,976.8 | 114,182.2 | 114,182.2 | 566,408.0 | 18,976.8 | 18,976.8 | 13,283.7 | 13,283.7 |
| 12 | 20,143.6 | 18,864.7 | 18,864.7 | 18,864.7 | 113,507.7 | 113,507.7 | 563,062.1 | 18,864.7 | 18,864.7 | 13,205.3 | 13,205.3 |
| 13 | 19,315.8 | 18,089.4 | 18,089.4 | 18,089.4 | 108,843.0 | 108,843.0 | 539,922.6 | 18,089.4 | 18,089.4 | 12,662.6 | 12,662.6 |
| night | 15,360.7 | 14,385.4 | 14,385.4 | 14,385.4 | 86,556.1 | 86,556.1 | 429,367.0 | 14,385.4 | 14,385.4 | 10,069.8 | 10,069.8 |

Annual fuel cost (USD)

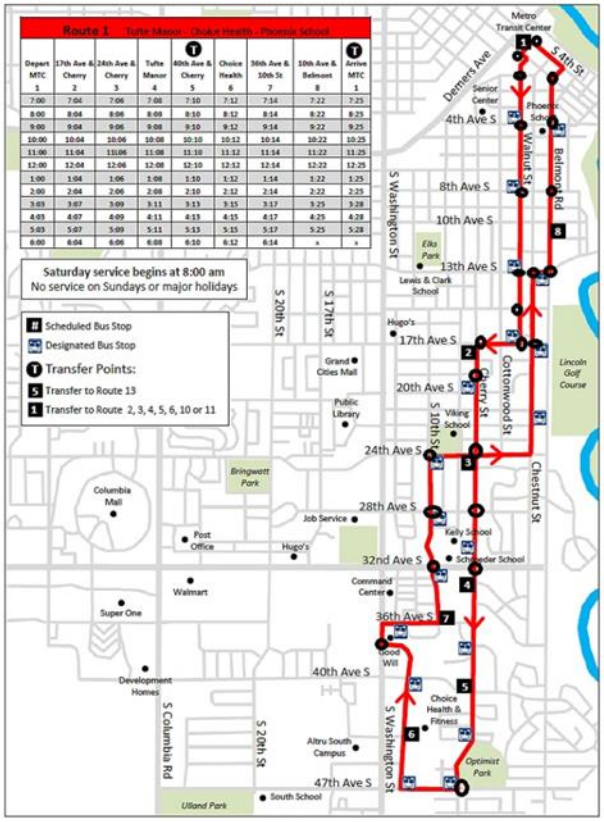
| BN/RN | 91 | 112 | 114 | 113 | 31 | 42 | 976 | 105 | 106 | 103 | 104 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 17,771.13 | 16,491.41 | 16,055.13 | 16,857.89 | 19,545.75 | 28,897.21 | 27,648.21 | 30,726.94 | 32,501.02 | 24,996.34 | 23,146.28 |
| 2 | 14,386.1 | 13,350.1 | 12,997.01 | 13,646.86 | 15,822.75 | 23,392.98 | 22,381.89 | 24,874.19 | 26,310.35 | 20,235.13 | 18,737.47 |
| 3 | 27,079.8 | 25,129.7 | 24,464.97 | 25,688.21 | 29,784.00 | 44,033.84 | 42,130.61 | 46,822.01 | 49,525.36 | 38,089.66 | 35,270.53 |
| 4 | 14,386.1 | 13,350.1 | 12,997.01 | 13,646.86 | 15,822.75 | 23,392.98 | 22,381.89 | 24,874.19 | 26,310.35 | 20,235.13 | 18,737.47 |
| 5 | 32,844.8 | 30,479.6 | 29,673.33 | 31,156.99 | 36,124.73 | 53,408.23 | 51,099.82 | 56,789.98 | 60,068.84 | 46,198.59 | 42,779.29 |
| 6 | 14,809.2 | 13,742.8 | 13,379.28 | 14,048.24 | 16,288.13 | 24,081.01 | 23,040.18 | 25,605.79 | 27,084.18 | 20,830.28 | 19,288.57 |
| 8 | 16,713.3 | 15,509.7 | 15,099.47 | 15,854.44 | 18,382.31 | 27,177.14 | 26,002.49 | 28,897.96 | 30,566.43 | 23,508.46 | 21,768.53 |
| 9 | 14,386.1 | 13,350.1 | 12,997.01 | 13,646.86 | 15,822.75 | 23,392.98 | 22,381.89 | 24,874.19 | 26,310.35 | 20,235.13 | 18,737.47 |
| 10 | 16,078.6 | 14,920.8 | 14,526.07 | 15,252.38 | 17,684.25 | 26,145.09 | 25,015.05 | 27,800.57 | 29,405.68 | 22,615.74 | 20,941.88 |
| 11 | 15,535.7 | 14,416.9 | 14,035.59 | 14,737.37 | 17,087.13 | 25,262.28 | 24,170.39 | 26,861.86 | 28,412.77 | 21,852.10 | 20,234.75 |
| 12 | 15,443.9 | 14,331.8 | 13,952.68 | 14,650.31 | 16,986.19 | 25,113.05 | 24,027.61 | 26,703.18 | 28,244.93 | 21,723.01 | 20,115.22 |
| 13 | 14,809.2 | 13,742.8 | 13,379.28 | 14,048.24 | 16,288.13 | 24,081.01 | 23,040.18 | 25,605.79 | 27,084.18 | 20,830.28 | 19,288.57 |
| night | 11,776.9 | 10,928.8 | 10,639.71 | 11,171.70 | 12,952.94 | 19,150.13 | 18,322.43 | 20,362.70 | 21,538.37 | 16,565.04 | 15,339.00 |

Combined preferability index equation

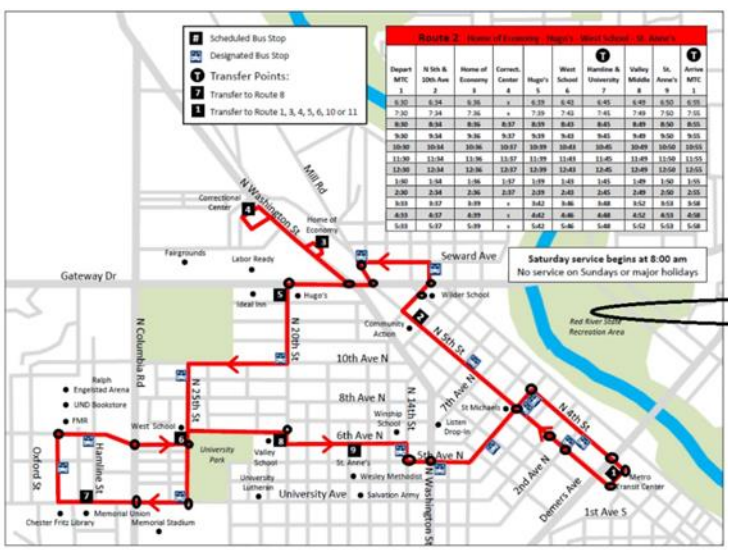
| BN/RN | 91 | 112 | 114 | 113 | 31 | 42 | 976 | 105 | 106 | 103 | 104 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.331 | 0.355 | 0.355 | 0.333 | 0.238 | 0.186 | 0.177 | 0.208 | 0.202 | 0.279 | 0.289 |
| 2 | 0.438 | 0.469 | 0.468 | 0.436 | 0.313 | 0.250 | 0.237 | 0.274 | 0.266 | 0.362 | 0.374 |
| 3 | 0.644 | 0.691 | 0.683 | 0.625 | 0.469 | 0.392 | 0.374 | 0.377 | 0.365 | 0.445 | 0.453 |
| 4 | 0.419 | 0.449 | 0.448 | 0.419 | 0.300 | 0.238 | 0.226 | 0.263 | 0.255 | 0.351 | 0.363 |
| 5 | 0.293 | 0.313 | 0.313 | 0.291 | 0.213 | 0.170 | 0.163 | 0.175 | 0.169 | 0.221 | 0.227 |
| 6 | 0.445 | 0.477 | 0.475 | 0.442 | 0.318 | 0.256 | 0.242 | 0.277 | 0.269 | 0.364 | 0.375 |
| 8 | 0.432 | 0.463 | 0.461 | 0.428 | 0.309 | 0.250 | 0.237 | 0.267 | 0.259 | 0.345 | 0.355 |
| 9 | 0.379 | 0.405 | 0.406 | 0.382 | 0.272 | 0.212 | 0.202 | 0.241 | 0.233 | 0.327 | 0.339 |
| 10 | 0.417 | 0.447 | 0.445 | 0.415 | 0.298 | 0.239 | 0.227 | 0.259 | 0.251 | 0.339 | 0.350 |
| 11 | 0.320 | 0.343 | 0.345 | 0.326 | 0.231 | 0.176 | 0.168 | 0.205 | 0.199 | 0.285 | 0.296 |
| 12 | 0.274 | 0.293 | 0.296 | 0.283 | 0.198 | 0.146 | 0.140 | 0.179 | 0.173 | 0.258 | 0.270 |
| 13 | 0.290 | 0.310 | 0.314 | 0.299 | 0.210 | 0.155 | 0.149 | 0.190 | 0.184 | 0.272 | 0.284 |
| night | 0.349 | 0.373 | 0.378 | 0.361 | 0.254 | 0.186 | 0.179 | 0.231 | 0.223 | 0.333 | 0.349 |

## APPENDIX B: Bus routes with stop information

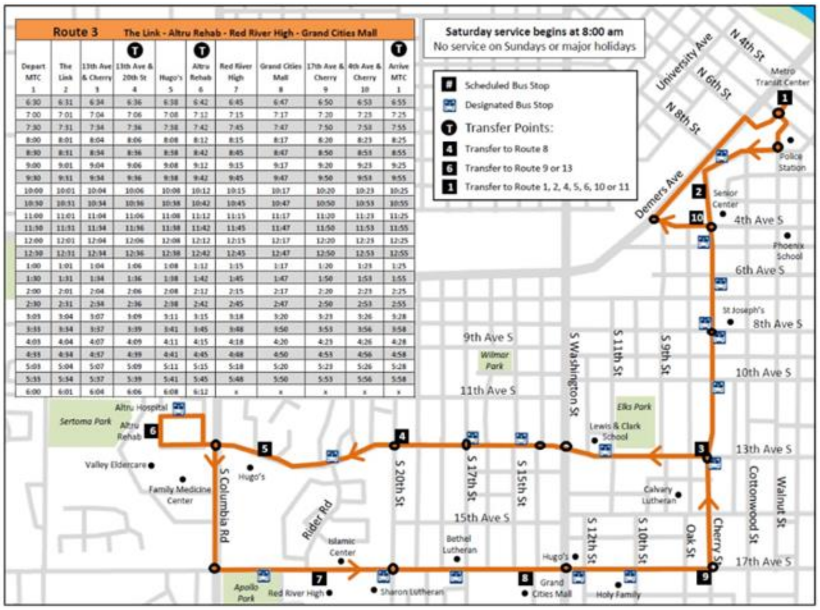
Route 1




Route 2



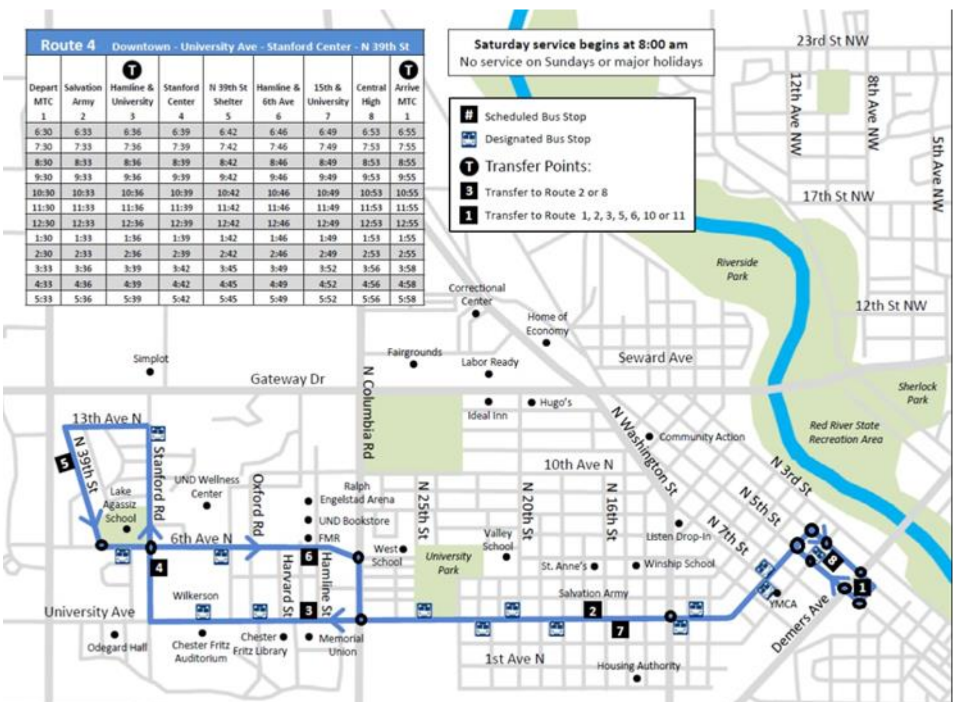
Route 3




**Route 3** The Link - Altru Rehab - Red River High - Grand Cities Mall

| Depart MTC 1 | The Link 2 | 13th Ave & Cherry 3 | 13th Ave & 20th St 4 | Hugo's 5 | Altru Rehab 6 | Red River High 7 | Grand Cities Mall 8 | 17th Ave & Cherry 9 | 4th Ave & Cherry 10 | Arrive MTC 1 |
|---|---|---|---|---|---|---|---|---|---|---|
| 6:30 | 6:31 | 6:34 | 6:36 | 6:38 | 6:42 | 6:45 | 6:47 | 6:50 | 6:53 | 6:55 |
| 7:00 | 7:01 | 7:04 | 7:06 | 7:08 | 7:12 | 7:15 | 7:17 | 7:20 | 7:23 | 7:25 |
| 7:30 | 7:31 | 7:34 | 7:36 | 7:38 | 7:42 | 7:45 | 7:47 | 7:50 | 7:53 | 7:55 |
| 8:00 | 8:01 | 8:04 | 8:06 | 8:08 | 8:12 | 8:15 | 8:17 | 8:20 | 8:23 | 8:25 |
| 8:30 | 8:31 | 8:34 | 8:36 | 8:38 | 8:42 | 8:45 | 8:47 | 8:50 | 8:53 | 8:55 |
| 9:00 | 9:01 | 9:04 | 9:06 | 9:08 | 9:12 | 9:15 | 9:17 | 9:20 | 9:23 | 9:25 |
| 9:30 | 9:31 | 9:34 | 9:36 | 9:38 | 9:42 | 9:45 | 9:47 | 9:50 | 9:53 | 9:55 |
| 10:00 | 10:01 | 10:04 | 10:06 | 10:08 | 10:12 | 10:15 | 10:17 | 10:20 | 10:23 | 10:25 |
| 10:30 | 10:31 | 10:34 | 10:36 | 10:38 | 10:42 | 10:45 | 10:47 | 10:50 | 10:53 | 10:55 |
| 11:00 | 11:01 | 11:04 | 11:06 | 11:08 | 11:12 | 11:15 | 11:17 | 11:20 | 11:23 | 11:25 |
| 11:30 | 11:31 | 11:34 | 11:36 | 11:38 | 11:42 | 11:45 | 11:47 | 11:50 | 11:53 | 11:55 |
| 12:00 | 12:01 | 12:04 | 12:06 | 12:08 | 12:12 | 12:15 | 12:17 | 12:20 | 12:23 | 12:25 |
| 12:30 | 12:31 | 12:34 | 12:36 | 12:38 | 12:42 | 12:45 | 12:47 | 12:50 | 12:53 | 12:55 |
| 1:00 | 1:01 | 1:04 | 1:06 | 1:08 | 1:12 | 1:15 | 1:17 | 1:20 | 1:23 | 1:25 |
| 1:30 | 1:31 | 1:34 | 1:36 | 1:38 | 1:42 | 1:45 | 1:47 | 1:50 | 1:53 | 1:55 |
| 2:00 | 2:01 | 2:04 | 2:06 | 2:08 | 2:12 | 2:15 | 2:17 | 2:20 | 2:23 | 2:25 |
| 2:30 | 2:31 | 2:34 | 2:36 | 2:38 | 2:42 | 2:45 | 2:47 | 2:50 | 2:53 | 2:55 |
| 3:03 | 3:04 | 3:07 | 3:09 | 3:11 | 3:15 | 3:18 | 3:20 | 3:23 | 3:26 | 3:28 |
| 3:33 | 3:34 | 3:37 | 3:39 | 3:41 | 3:45 | 3:48 | 3:50 | 3:53 | 3:56 | 3:58 |
| 4:03 | 4:04 | 4:07 | 4:09 | 4:11 | 4:15 | 4:18 | 4:20 | 4:23 | 4:26 | 4:28 |
| 4:33 | 4:34 | 4:37 | 4:39 | 4:41 | 4:45 | 4:48 | 4:50 | 4:53 | 4:56 | 4:58 |
| 5:03 | 5:04 | 5:07 | 5:09 | 5:11 | 5:15 | 5:18 | 5:20 | 5:23 | 5:26 | 5:28 |
| 5:33 | 5:34 | 5:37 | 5:39 | 5:41 | 5:45 | 5:48 | 5:50 | 5:53 | 5:56 | 5:58 |
| 6:00 | 6:01 | 6:04 | 6:06 | 6:08 | 6:12 | x | x | x | x | x |

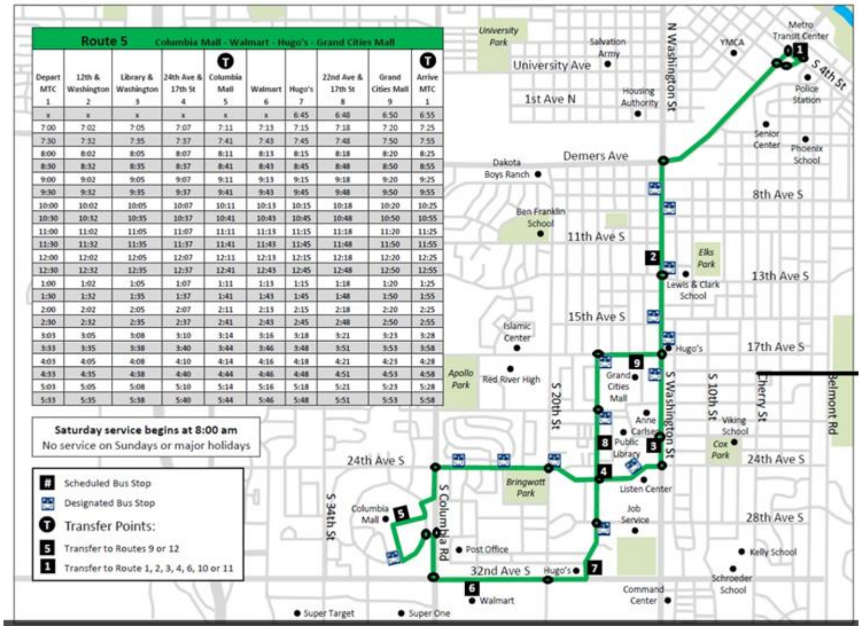
Route 4




**Route 4** Downtown - University Ave - Stanford Center - N 39th St

| Depart MTC 1 | Salvation Army 2 | Hamline & University 3 | Stanford Center 4 | N 39th St Shelter 5 | Hamline & 6th Ave 6 | 15th & University 7 | Central High 8 | Arrive MTC 1 |
|---|---|---|---|---|---|---|---|---|
| 6:30 | 6:33 | 6:36 | 6:39 | 6:42 | 6:46 | 6:49 | 6:53 | 6:55 |
| 7:30 | 7:33 | 7:36 | 7:39 | 7:42 | 7:46 | 7:49 | 7:53 | 7:55 |
| 8:30 | 8:33 | 8:36 | 8:39 | 8:42 | 8:46 | 8:49 | 8:53 | 8:55 |
| 9:30 | 9:33 | 9:36 | 9:39 | 9:42 | 9:46 | 9:49 | 9:53 | 9:55 |
| 10:30 | 10:33 | 10:36 | 10:39 | 10:42 | 10:46 | 10:49 | 10:53 | 10:55 |
| 11:30 | 11:33 | 11:36 | 11:39 | 11:42 | 11:46 | 11:49 | 11:53 | 11:55 |
| 12:30 | 12:33 | 12:36 | 12:39 | 12:42 | 12:46 | 12:49 | 12:53 | 12:55 |
| 1:30 | 1:33 | 1:36 | 1:39 | 1:42 | 1:46 | 1:49 | 1:53 | 1:55 |
| 2:30 | 2:33 | 2:36 | 2:39 | 2:42 | 2:46 | 2:49 | 2:53 | 2:55 |
| 3:33 | 3:36 | 3:39 | 3:42 | 3:45 | 3:49 | 3:52 | 3:56 | 3:58 |
| 4:33 | 4:36 | 4:39 | 4:42 | 4:45 | 4:49 | 4:52 | 4:56 | 4:58 |
| 5:33 | 5:36 | 5:39 | 5:42 | 5:45 | 5:49 | 5:52 | 5:56 | 5:58 |

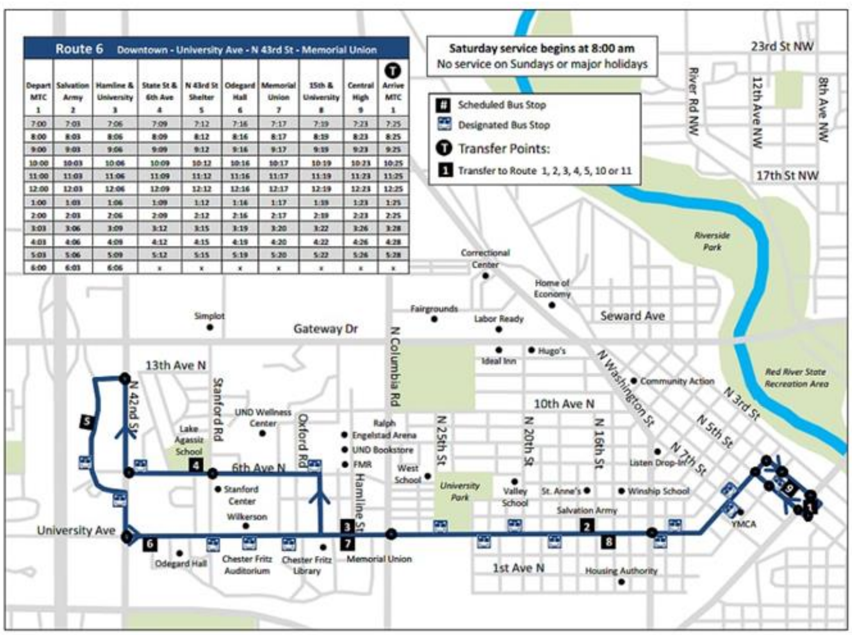
Route 5




**Route 5** Columbia Mall - Walmart - Hugo's - Grand Cities Mall

| Depart MTC 1 | 12th & Washington 2 | Library & Washington 3 | 24th Ave & 17th St 4 | Columbia Mall 5 | Walmart 6 | Hugo's 7 | 22nd Ave & 17th St 8 | Grand Cities Mall 9 | Arrive MTC 1 |
|---|---|---|---|---|---|---|---|---|---|
| x | x | x | x | x | x | 6:45 | 6:48 | 6:50 | 6:55 |
| 7:00 | 7:02 | 7:05 | 7:07 | 7:11 | 7:13 | 7:15 | 7:18 | 7:20 | 7:25 |
| 7:30 | 7:32 | 7:35 | 7:37 | 7:41 | 7:43 | 7:45 | 7:48 | 7:50 | 7:55 |
| 8:00 | 8:02 | 8:05 | 8:07 | 8:11 | 8:13 | 8:15 | 8:18 | 8:20 | 8:25 |
| 8:30 | 8:32 | 8:35 | 8:37 | 8:41 | 8:43 | 8:45 | 8:48 | 8:50 | 8:55 |
| 9:00 | 9:02 | 9:05 | 9:07 | 9:11 | 9:13 | 9:15 | 9:18 | 9:20 | 9:25 |
| 9:30 | 9:32 | 9:35 | 9:37 | 9:41 | 9:43 | 9:45 | 9:48 | 9:50 | 9:55 |
| 10:00 | 10:02 | 10:05 | 10:07 | 10:11 | 10:13 | 10:15 | 10:18 | 10:20 | 10:25 |
| 10:30 | 10:32 | 10:35 | 10:37 | 10:41 | 10:43 | 10:45 | 10:48 | 10:50 | 10:55 |
| 11:00 | 11:02 | 11:05 | 11:07 | 11:11 | 11:13 | 11:15 | 11:18 | 11:20 | 11:25 |
| 11:30 | 11:32 | 11:35 | 11:37 | 11:41 | 11:43 | 11:45 | 11:48 | 11:50 | 11:55 |
| 12:00 | 12:02 | 12:05 | 12:07 | 12:11 | 12:13 | 12:15 | 12:18 | 12:20 | 12:25 |
| 12:30 | 12:32 | 12:35 | 12:37 | 12:41 | 12:43 | 12:45 | 12:48 | 12:50 | 12:55 |
| 1:00 | 1:02 | 1:05 | 1:07 | 1:11 | 1:13 | 1:15 | 1:18 | 1:20 | 1:25 |
| 1:30 | 1:32 | 1:35 | 1:37 | 1:41 | 1:43 | 1:45 | 1:48 | 1:50 | 1:55 |
| 2:00 | 2:02 | 2:05 | 2:07 | 2:11 | 2:13 | 2:15 | 2:18 | 2:20 | 2:25 |
| 2:30 | 2:32 | 2:35 | 2:37 | 2:41 | 2:43 | 2:45 | 2:48 | 2:50 | 2:55 |
| 3:03 | 3:05 | 3:08 | 3:10 | 3:14 | 3:16 | 3:18 | 3:21 | 3:23 | 3:28 |
| 3:33 | 3:35 | 3:38 | 3:40 | 3:44 | 3:46 | 3:48 | 3:51 | 3:53 | 3:58 |
| 4:03 | 4:05 | 4:08 | 4:10 | 4:14 | 4:16 | 4:18 | 4:21 | 4:23 | 4:28 |
| 4:33 | 4:35 | 4:38 | 4:40 | 4:44 | 4:46 | 4:48 | 4:51 | 4:53 | 4:58 |
| 5:03 | 5:05 | 5:08 | 5:10 | 5:14 | 5:16 | 5:18 | 5:21 | 5:23 | 5:28 |
| 5:33 | 5:35 | 5:38 | 5:40 | 5:44 | 5:46 | 5:48 | 5:51 | 5:53 | 5:58 |

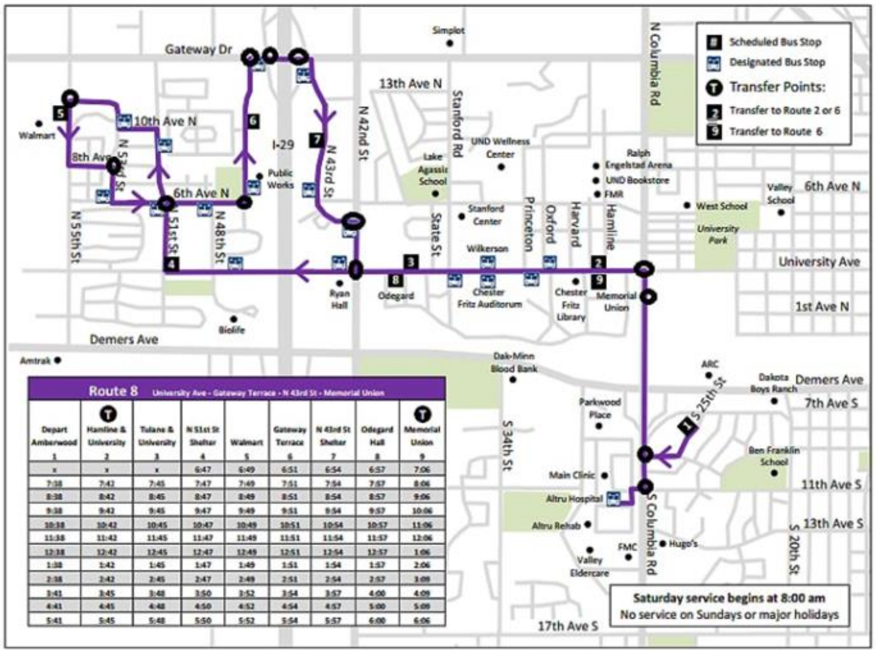
Route 6




**Route 6** Downtown - University Ave - N 43rd St - Memorial Union

| Depart MTC 1 | Salvation Army 2 | Hamline & University 3 | State St & 6th Ave 4 | N 43rd St Shelter 5 | Odegard Hall 6 | Memorial Union 7 | 15th & University 8 | Central High 9 | Arrive MTC 1 |
|---|---|---|---|---|---|---|---|---|---|
| 7:00 | 7:03 | 7:06 | 7:09 | 7:12 | 7:16 | 7:17 | 7:19 | 7:23 | 7:25 |
| 8:00 | 8:03 | 8:06 | 8:09 | 8:12 | 8:16 | 8:17 | 8:19 | 8:23 | 8:25 |
| 9:00 | 9:03 | 9:06 | 9:09 | 9:12 | 9:16 | 9:17 | 9:19 | 9:23 | 9:25 |
| 10:00 | 10:03 | 10:06 | 10:09 | 10:12 | 10:16 | 10:17 | 10:19 | 10:23 | 10:25 |
| 11:00 | 11:03 | 11:06 | 11:09 | 11:12 | 11:16 | 11:17 | 11:19 | 11:23 | 11:25 |
| 12:00 | 12:03 | 12:06 | 12:09 | 12:12 | 12:16 | 12:17 | 12:19 | 12:23 | 12:25 |
| 1:00 | 1:03 | 1:06 | 1:09 | 1:12 | 1:16 | 1:17 | 1:19 | 1:23 | 1:25 |
| 2:00 | 2:03 | 2:06 | 2:09 | 2:12 | 2:16 | 2:17 | 2:19 | 2:23 | 2:25 |
| 3:03 | 3:06 | 3:09 | 3:12 | 3:15 | 3:19 | 3:20 | 3:22 | 3:26 | 3:28 |
| 4:03 | 4:06 | 4:09 | 4:12 | 4:15 | 4:19 | 4:20 | 4:22 | 4:26 | 4:28 |
| 5:03 | 5:06 | 5:09 | 5:12 | 5:15 | 5:19 | 5:20 | 5:22 | 5:26 | 5:28 |
| 6:00 | 6:03 | 6:06 | x | x | x | x | x | x | x |

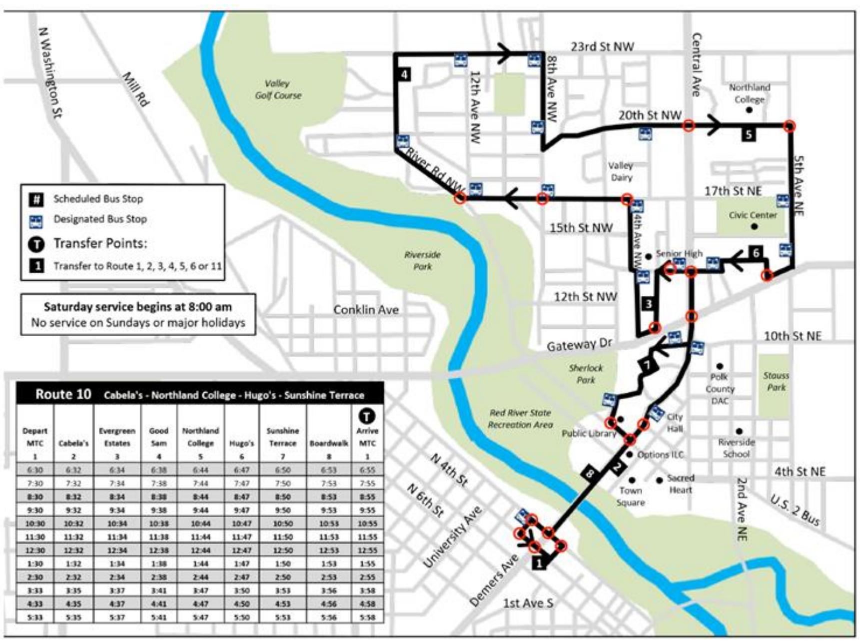
Route 8




**Route 8** University Ave - Gateway Terrace - N 43rd St - Memorial Union

| Depart Amberwood 1 | Hamline & University 2 | Tulane & University 3 | N 51st St Shelter 4 | Walmart 5 | Gateway Terrace 6 | N 43rd St Shelter 7 | Odegard Hall 8 | Memorial Union 9 |
|---|---|---|---|---|---|---|---|---|
| x | x | x | 6:47 | 6:49 | 6:51 | 6:54 | 6:57 | 7:06 |
| 7:38 | 7:42 | 7:45 | 7:47 | 7:49 | 7:51 | 7:54 | 7:57 | 8:06 |
| 8:38 | 8:42 | 8:45 | 8:47 | 8:49 | 8:51 | 8:54 | 8:57 | 9:06 |
| 9:38 | 9:42 | 9:45 | 9:47 | 9:49 | 9:51 | 9:54 | 9:57 | 10:06 |
| 10:38 | 10:42 | 10:45 | 10:47 | 10:49 | 10:51 | 10:54 | 10:57 | 11:06 |
| 11:38 | 11:42 | 11:45 | 11:47 | 11:49 | 11:51 | 11:54 | 11:57 | 12:06 |
| 12:38 | 12:42 | 12:45 | 12:47 | 12:49 | 12:51 | 12:54 | 12:57 | 1:06 |
| 1:38 | 1:42 | 1:45 | 1:47 | 1:49 | 1:51 | 1:54 | 1:57 | 2:06 |
| 2:38 | 2:42 | 2:45 | 2:47 | 2:49 | 2:51 | 2:54 | 2:57 | 3:09 |
| 3:41 | 3:45 | 3:48 | 3:50 | 3:52 | 3:54 | 3:57 | 4:00 | 4:09 |
| 4:41 | 4:45 | 4:48 | 4:50 | 4:52 | 4:54 | 4:57 | 5:00 | 5:09 |
| 5:41 | 5:45 | 5:48 | 5:50 | 5:52 | 5:54 | 5:57 | 6:00 | 6:06 |

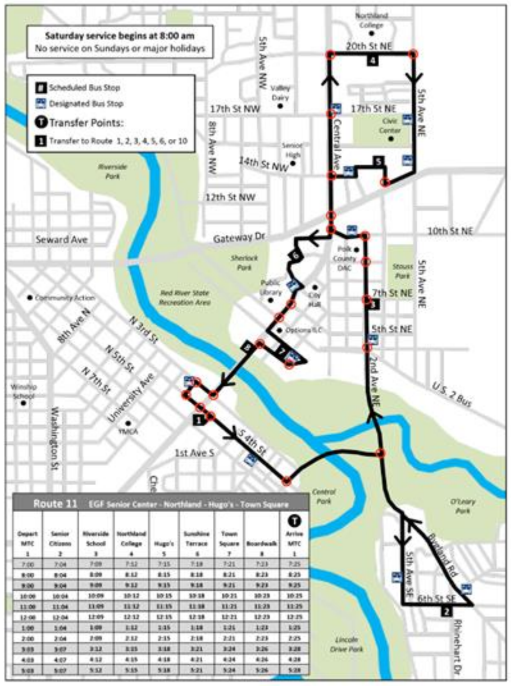
Route 10




**Route 10** Cabela's - Northland College - Hugo's - Sunshine Terrace

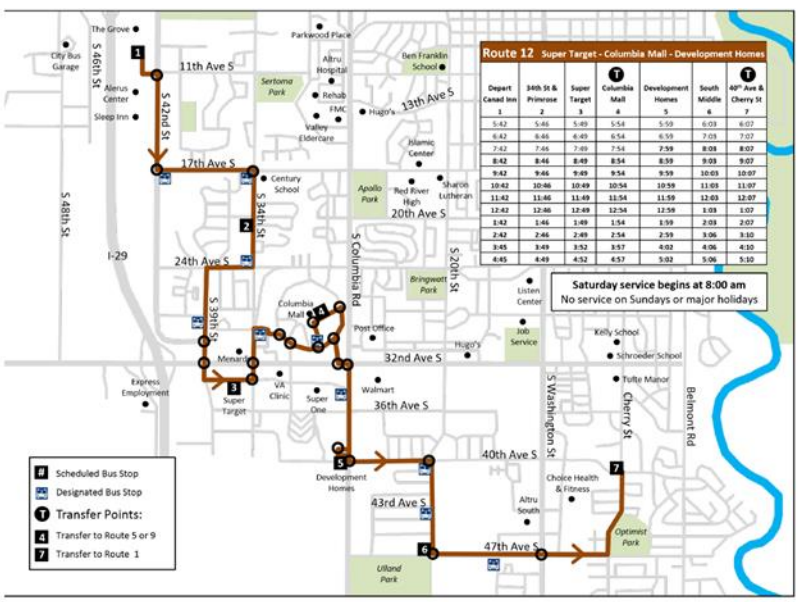
| Depart MTC 1 | Cabela's 2 | Evergreen Estates 3 | Good Sam 4 | Northland College 5 | Hugo's 6 | Sunshine Terrace 7 | Boardwalk 8 | Arrive MTC 1 |
|---|---|---|---|---|---|---|---|---|
| 6:30 | 6:32 | 6:34 | 6:38 | 6:44 | 6:47 | 6:50 | 6:53 | 6:55 |
| 7:30 | 7:32 | 7:34 | 7:38 | 7:44 | 7:47 | 7:50 | 7:53 | 7:55 |
| 8:30 | 8:32 | 8:34 | 8:38 | 8:44 | 8:47 | 8:50 | 8:53 | 8:55 |
| 9:30 | 9:32 | 9:34 | 9:38 | 9:44 | 9:47 | 9:50 | 9:53 | 9:55 |
| 10:30 | 10:32 | 10:34 | 10:38 | 10:44 | 10:47 | 10:50 | 10:53 | 10:55 |
| 11:30 | 11:32 | 11:34 | 11:38 | 11:44 | 11:47 | 11:50 | 11:53 | 11:55 |
| 12:30 | 12:32 | 12:34 | 12:38 | 12:44 | 12:47 | 12:50 | 12:53 | 12:55 |
| 1:30 | 1:32 | 1:34 | 1:38 | 1:44 | 1:47 | 1:50 | 1:53 | 1:55 |
| 2:30 | 2:32 | 2:34 | 2:38 | 2:44 | 2:47 | 2:50 | 2:53 | 2:55 |
| 3:33 | 3:35 | 3:37 | 3:41 | 3:47 | 3:50 | 3:53 | 3:56 | 3:58 |
| 4:33 | 4:35 | 4:37 | 4:41 | 4:47 | 4:50 | 4:53 | 4:56 | 4:58 |
| 5:33 | 5:35 | 5:37 | 5:41 | 5:47 | 5:50 | 5:53 | 5:56 | 5:58 |

Route 11



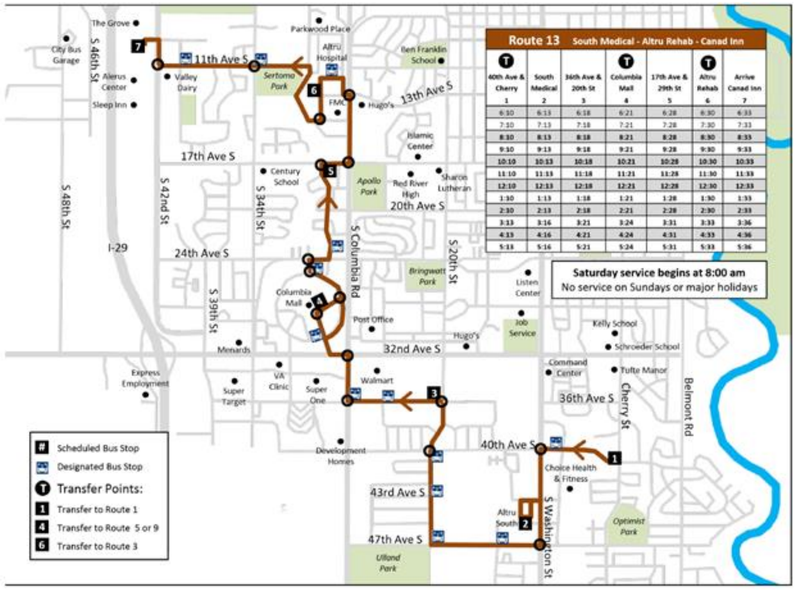

| Route 11 EGF Senior Center - Northland - Hugo's - Town Square | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Depart MTC 1 | Senior Citizens 2 | Riverside School 3 | Northland College 4 | Hugo's 5 | Sunshine Terrace 6 | Town Square 7 | Boardwalk 8 | Arrive MTC 1 |
| 7:00 | 7:04 | 7:09 | 7:12 | 7:15 | 7:18 | 7:21 | 7:23 | 7:25 |
| 8:00 | 8:04 | 8:09 | 8:12 | 8:15 | 8:18 | 8:21 | 8:23 | 8:25 |
| 9:00 | 9:04 | 9:09 | 9:12 | 9:15 | 9:18 | 9:21 | 9:23 | 9:25 |
| 10:00 | 10:04 | 10:09 | 10:12 | 10:15 | 10:18 | 10:21 | 10:23 | 10:25 |
| 11:00 | 11:04 | 11:09 | 11:12 | 11:15 | 11:18 | 11:21 | 11:23 | 11:25 |
| 12:00 | 12:04 | 12:09 | 12:12 | 12:15 | 12:18 | 12:21 | 12:23 | 12:25 |
| 1:00 | 1:04 | 1:09 | 1:12 | 1:15 | 1:18 | 1:21 | 1:23 | 1:25 |
| 2:00 | 2:04 | 2:09 | 2:12 | 2:15 | 2:18 | 2:21 | 2:23 | 2:25 |
| 3:03 | 3:07 | 3:12 | 3:15 | 3:18 | 3:21 | 3:24 | 3:26 | 3:28 |
| 4:03 | 4:07 | 4:12 | 4:15 | 4:18 | 4:21 | 4:24 | 4:26 | 4:28 |
| 5:03 | 5:07 | 5:12 | 5:15 | 5:18 | 5:21 | 5:24 | 5:26 | 5:28 |

Route 12

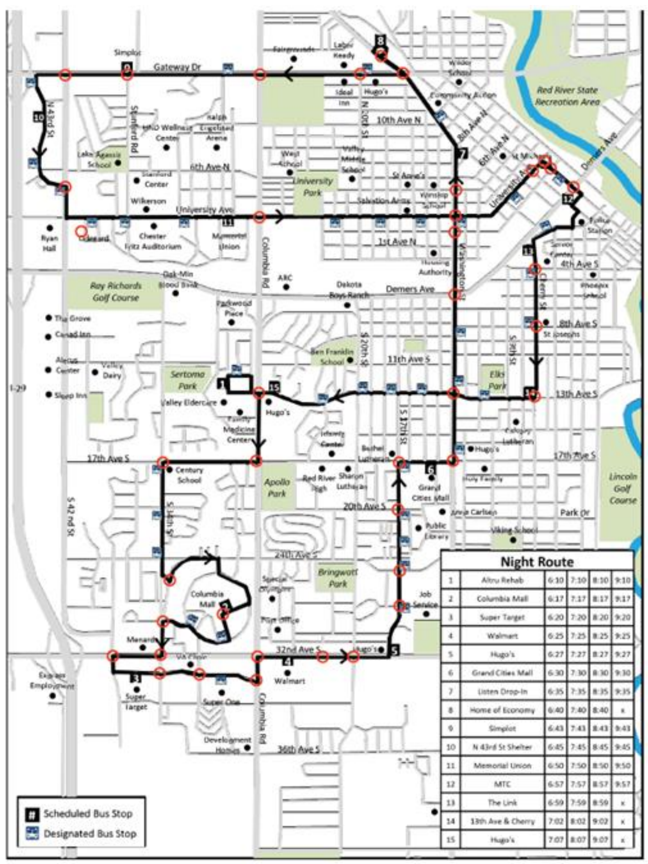



| Route 12 Super Target - Columbia Mall - Development Homes | | | | | | |
|---|---|---|---|---|---|---|
| Depart Canad Inn 1 | 34th St & Primrose 2 | Super Target 3 | Columbia Mall 4 | Development Homes 5 | South Middle 6 | 40th Ave & Cherry St 7 |
| 5:42 | 5:46 | 5:49 | 5:54 | 5:59 | 6:03 | 6:07 |
| 6:42 | 6:46 | 6:49 | 6:54 | 6:59 | 7:03 | 7:07 |
| 7:42 | 7:46 | 7:49 | 7:54 | 7:59 | 8:03 | 8:07 |
| 8:42 | 8:46 | 8:49 | 8:54 | 8:59 | 9:03 | 9:07 |
| 9:42 | 9:46 | 9:49 | 9:54 | 9:59 | 10:03 | 10:07 |
| 10:42 | 10:46 | 10:49 | 10:54 | 10:59 | 11:03 | 11:07 |
| 11:42 | 11:46 | 11:49 | 11:54 | 11:59 | 12:03 | 12:07 |
| 12:42 | 12:46 | 12:49 | 12:54 | 12:59 | 1:03 | 1:07 |
| 1:42 | 1:46 | 1:49 | 1:54 | 1:59 | 2:03 | 2:07 |
| 2:42 | 2:46 | 2:49 | 2:54 | 2:59 | 3:06 | 3:10 |
| 3:45 | 3:49 | 3:52 | 3:57 | 4:02 | 4:06 | 4:10 |
| 4:45 | 4:49 | 4:52 | 4:57 | 5:02 | 5:06 | 5:10 |

Route 13




Night bus



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