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ORIGINAL RESEARCH

Analytical models for comparing operational costs of regular bus and semi-flexible transit services

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Abstract
The provision of public transit services is essential to provide citizens with an improved quality of life. The most popular fixed route bus service (FRBS) is intended to serve a large population along with fixed stops, routes, and schedules. However, in low demand conditions, bus transit operators pay a high cost per passenger to maintain the desired level of service. A demand-responsive transit (DRT) is a commonly discussed transportation solution for serving low passenger demand. Although the conventional DRT system offers a shared-ride door-to-door service to passengers, its implementation is challenging and expensive during peak hours. The present study suggests a form of transit system that combines the rigidity of FRBS and flexibility of DRT to operate in low demand routes. This defined category of transit service is referred to as semi-flexible transit (SFT) system. The proposed SFT service is delivered along the fixed bus route and a limited number of fixed stops based on a flexible schedule to meet passenger requests. The defined SFT system offers reduced operating time and higher vehicle utilization. The study considers an operation of the proposed SFT service for two types of service delivery systems: Contract-Out Taxi Service (COTS), and In-House Paratransit Service (IHPS). A methodology is proposed to develop analytical models describing operational costs of regular FRBS, COTS, and IHPS as a function of demand or annual ridership. Operating cost models are proposed as a decision support tool to enable transit planners to determine the passenger demands along the route at which it is justifiable to "switch" from FRBS to the SFT system to minimize the total cost of operation. Further, the analysis results for FRBS indicate that operating costs are strongly related to vehicle-service hours and for SFT services to average vehicle occupancy rate and deadheading time. Applications of the proposed models and analysis method are demonstrated for a low demand route in the City of Regina.

Keywords Demand-responsive transit · Flexible transit · Semi-flexible transit · Bus transit · Contract-out taxi service · In-house paratransit service · Operating costs · Economic performance

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1 Introduction

The provision to public transit services is essential to provide citizens equal access and affordability to transportation service; thus, promoting economic and sustainable development of a nation. Bus transit is the most popular form of public transportation, providing ground-level transportation service on a defined set of road networks. The conventional system of bus transit is intended to serve a large population along with fixed stops, routes and schedules; hence, also referred to as fixed route bus service (FRBS) (Vuchic 2017). These rigid systems perform efficiently in densely populated areas with the definite direction of travel, such as traveling to and from downtown. However, the recent trends in the growth of population and economy, and societal changes in North America have contributed to the creation of low-demand suburban areas. Statistics Canada records a population growth rate of 6.9% in smaller municipalities compared to 5.8% in larger municipalities from 2011 to 2016 (Statistics Canada 2016). The larger municipalities in the United States observed a reduction in population density, regardless of the increase in overall population growth (Meijers and Burger 2010). The observed phenomenon depreciates bus transit as it lacks flexibility in offering service to this dispersed population with distinct desire for a pick-up and/or drop-off location, route or schedule (Fittante and Lubin 2015). A bus following a fixed route has to traverse a large area to serve this dispersed population, resulting in increased transit operator expenses and travel time of passengers. Additionally, the low ridership offered during both peak and off-peak hours results in generating lower revenues for transit operators. Typically, the transit operators attempt to reduce the gap in operating expenses and revenue generated by increasing the fares or reducing the frequency of bus service in these areas. Consequently, a larger portion of the population in suburban areas is attracted to use private vehicles offering lesser travel time and cost for commuting, hence causing traffic congestion and pollution problems in urban areas (Turcotte 2008). However, regardless of issues in providing bus transit service to these areas, discontinuation of service is inappropriate; as access to public transportation is essential for citizens to maintain an acceptable standard of living. Thus, providing feasible and efficient public transit options for low demand areas is critical for bus transit agencies.

A demand-responsive transit (DRT) or Dial-a-Ride Transit (DART) system is a commonly discussed transportation solution for low passenger demand observed in suburban/rural areas, off-peak hours and weekends (Gupta et al. 2010). A DRT is a form of transit service where the vehicle deviates from its fixed route and enters into narrow local routes, to serve passengers demanding for their distinct pick-up or drop-off location. The passengers are assumed to book the service well in advance, such that the operator can arrange multiple pick-ups to ensure maximum utilization of the vehicle in each tour. Typically, in a DRT, a taxi or paratransit vehicle with fewer seats and smaller sizes are offered for service, which is more suitable to operate in low demand conditions while providing more flexibility for moving along narrower roads. Although DRT offers a shared-ride door-to-door service to passengers, its implementation is challenging and expensive during peak hours with more passengers requesting the service (Daganzo 1978;

Enoch et al. 2006). Thus, the application of this conventional form of DRT system is limited to serving smaller communities experiencing difficulty in accessing a bus such as older people, people with disabilities and the general public in very remote areas (Potts et al. 2010). The present study suggests a form of transit system that combines the rigidity of a FRBS and flexibility of DRT to operate in low demand routes. This defined category of transit service is referred to as semi-flexible transit (SFT) system. The proposed SFT service is delivered along the fixed bus route and a limited number of fixed stops based on a flexible schedule to meet passenger requests. Thus, a SFT system promotes cost savings by offering reduced operating time and increased vehicle capacity utilization. The defined service is intended to serve the general public, unlike the conventional DRT systems, which provide door-to-door accessible services. However, despite several associated positive implications, it is imperative to note that the proposed system is not efficient in providing door-to-door accessible services and requires transit operators to be equipped with specialized software and highly skilled personnel to manage the passenger requests and schedule the dispatch of a vehicle. Thus, the operation of the system by public or private transit agencies may be still expensive in its implementation. However, a recent increasing interest among public and private transit agencies to provide flexible transit services in-coordination, demands for practical mathematical models to assess the cost of providing service through these programs (Tsay et al. 2016). The present study derives analytical models to estimate operating costs of regular bus transit (FRBS) and the proposed SFT services, to evaluate the financial feasibility of providing the two transit systems based on demand. It is hypothesized that bus service is efficient for high-demand conditions, while taxi or paratransit services are preferred at low-demand conditions as they offer lower operating costs. This hypothesis is examined by determining the passenger demands along the route at which it is justifiable to "switch" from FRBS to the SFT system to minimize the total cost of operation. The analysis assists decision makers in identifying the best time in a day (or a week, month or season), to switch from one service type to another based on passenger demand patterns. Further, the study derives mathematical models for operating costs of proposed SFT service for two types of service delivery systems: Contract-Out Taxi Service (COTS), and In-House Paratransit Service (IHPS). COTS refers to a taxi service administered and operated by a private agency in a service contract with a government transit agency. IHPS refers to a paratransit service completely administered and operated by a government transit agency. The paratransit vehicles in this study are assumed to operate along a fixed route as per defined SFT system. However, the taxis are assumed to be flexible to adopt any route to the requested nearest fixed stop location. In essence, operational efficiency and financial feasibility of providing a FRBS, COTS, and IHPS are evaluated based on varying passenger demand for a low demand route. The proposed methodology is applied to a low demand bus route in Regina, the capital city of the Canadian province of Saskatchewan to demonstrate the application of the models. Furthermore, the proposed analysis methods enable evaluation of the operating costs considering the sensitivity in future demand, OD flows, and operating conditions subjected to changes in socio-economic factors, land use patterns, and local policies. Therefore, the study implication as a decision support tool enables transit planners to determine the conditions for switching between regular and flexible transit services in low demand conditions.

The remainder of the paper is organized as follows. Section 2 provides a brief review of the existing literature on demand-responsive systems and the metrics of efficiency for demand-responsive services. This is followed by Sect. 3 which discusses the methodology including system description and operating cost model formulation. Section 4 describes the study area and demonstrates the application of the proposed models. The section also includes a sensitivity analysis carried out to evaluate the response of cost models to variations in input variables. Section 5 eventually concludes the paper and provides a brief summary and recommendations for future research.

2 Literature review

The literature review for this study is organized in the following sub-sections representing two important aspects of the existing research.

2.1 Developments in demand-responsive operating policies

The past research studies suggest that a conventional DRT system is inefficient in serving the increasing demand for dial-a-ride services and paratransit services, specifically for older citizens (Cayford and Yim 2004). Thus, there is a pressing need for transportation agencies to adopt improved operating policies (Kaufman et al. 2016) or service delivery methods (KFH Group 2008) to reduce total agency operating costs. The present section discusses the transitions in demand-responsive operation attributed to the introduction of improved technology, zoning strategies, and routing policies. A survey including 67 large U.S. transit agencies investigated the impact of implementation of Advanced Communications systems, Paratransit Computer-Aided Dispatching (CAD) systems, and Advanced Public Transportation Systems (APTS) technologies in DRT systems (Palmer et al. 2004, 2008; Dessouky et al. 2003). The survey reported a reduced operating cost of approximately \$3.00 per passenger trip by using Advanced Communications technology. Additionally, the implementation of a Paratransit CAD system increased the annual productivity of the service (approximately by up to 12,000 passenger miles per vehicle, and 1100 trips per vehicle). The conventional system of DRT is designed to serve the population over a large service area for providing door-to-door service. Thus, several researchers have developed analytical models to divide a large service area into several smaller service zones; thus, improving both the productivity and service quality of DRT systems (Li and Quadrifoglio 2009; Wang et al. 2018; Aldaihani et al. 2004). Transit operations experts suggest that a flexible transit system that combines the regularity of bus transit and flexibility of taxi, is cost-efficient in serving the suburban or rural population (Koffman 2004). The referred study derives this conclusion based on a survey involving 51 North America transit operators located in 20 states of the US and 3 Canadian provinces. These transit operators generally provide flexible transit systems based on scheduled passenger requests and offer deviation from fixed route or stop locations as per the needs of the passengers at certain times. Flexible transit services primarily follow a many-to-one operating policy (i.e., many boarding stop locations but one alighting stop location) or a one-to-many operating policy. However, a conventional bus transit follows a many-to-many operating policy serving multiple boarding and alighting stop locations. Several studies in recent years have appreciated the concept of a flexible transit system providing flexibility in route, stop location, and/or schedule as compared to conventional bus transit (Quadrifoglio et al. 2008; Li and Quadrifoglio 2011; Nourbakhsh and Ouyang 2012; Häll et al. 2015; Qiu et al. 2015b; Yang et al. 2016; Navidi et al. 2018). Transit agencies providing flexible services for the general public often operate the service in coordination with fixed route bus transit (Potts et al. 2010). The flexible transit operating on a low demand route often moves passengers to a terminal point connecting to a major bus transit route. Additionally, when passenger demand is low, transit agencies may adjust daily bus service hours and switch to a flexible service to minimize the total operating cost. Several studies attempted to derive passenger demand density along the route when the cost of providing bus transit and flexible transit are equivalent, i.e., it is desirable to "switch" from one service type to another providing reduced cost of service (Quadrifoglio and Li 2009; Diana et al. 2009; Li and Quadrifoglio 2010; Qiu et al. 2015a). Similarly, a study in Atlanta used a dataset including 10% of Metropolitan Atlanta Rapid Transit Authority passenger surveys and developed a methodology to compare the performance of fixed route buses and flexible over a wide variety of streets and transit service layouts (Edwards and Watkins 2013). The present study also attempts to determine the passenger demand (i.e. ridership) at which it is desirable to shift from the proposed SFT service to FRBS for a low-demand bus transit route.

2.2 Demand-responsive service delivery systems

This section of the literature review includes the studies related to transit delivery systems implemented to minimize the operating cost of demand-responsive operations by providing a coordinated service between public and private service providers. The transit agencies over the past years have partnered taxi companies to supplement the public transportation with accessible services to disabled passengers, enabling to reduce the costs of operating paratransit services (Chia 2008; Burkhardt 2010; Tuttle and Eaton 2012; Ellis 2016). Recently, the taxi transportation network companies (TNCs) are performing efficiently in serving multiple passengers by using advanced automated systems for routing and scheduling of multiple passenger requests. Thus, there is an increasing interest among TNCs to provide DRT services in coordination with transit network agencies to reduce the total cost of operation (Taylor et al. 2015; Feigon and Murphy 2016; Tsay et al. 2016). A few studies in recent years have derived analytical operating cost models to evaluate DRT service provided in coordination with transit agencies and TNCs (Turmo et al. 2018; Rahimi et al. 2018; Goodwill and Carapella 2008). The referred studies suggest reduced operating cost of DRT service on contracting a proportion of trips to TNCs implementing effective automated routing and scheduling techniques. Further, a study in Portland, Oregon suggests a reduction in operating cost of DRT on switching service from in-house to contracted management, due to a reduction in a number of required personnel (Rufolo et al. 1996). The existing literature suggests a limited number of studies evaluating the provision of DRT services for older people and people with disabilities; in coordination with transit agencies and TNCs. However, there exists no previous research on evaluating the provision of flexible transit system to serve general public under different service delivery systems. The present study compares the operational efficiency of fixed-route bus transit with proposed SFT service for two types of service delivery systems, i.e. COTS and IHPS.

3 Methodology

3.1 Transit operating system definition

The transit operating systems considered are FRBS and SFT. The study considers the integration of FRBS operated by public transit agencies and SFT operated by public or private transit agencies exclusively or in coordination. The FRBS system operates similar to regular bus transit, offering continuous two-way service from fixed terminal stations along a fixed route, stops, and schedule.

The SFT system includes two distinct types of service delivery systems namely: COTS, and IHPS. The present study defines a SFT system that offers a shared ride service to passengers characterized with the fixed route, fixed pick-up and drop-off locations (same as fixed bus stops), and flexible schedules. The passengers are assumed to place service requests well in advance, such that the operator can arrange multiple pick-ups to ensure maximum utilization of the vehicle in each trip. The passengers are picked-up and dropped-off at predefined bus stop locations nearest to their preferred trip origins and destinations, respectively. Further, the dispatching scheme of SFT vehicle is a function of desired vehicle occupancy and maximum waiting time to account for operational feasibility and desired service quality, respectively. The study assumes SFT service to operate along the shortest paths between trip origins and destinations, serving multiple pick up and drop off locations in a single trip. Typically, the vehicles offered in COTS and IHPS services include taxi and van or mini-bus with fewer seats and smaller size than regular bus transit, respectively.

3.2 Cost model assumptions

Analytical cost models are developed for FRBS, COTS, and IHPS transit systems, to describe the operating costs (dependent variable) as a function of ridership (i.e. passenger demand) and other service-specific parameters (independent variables). The operating cost models enable detailed comparison of FRBS and SFT systems (i.e. COTS and IHPS) to determine the ridership thresholds to switch from one service to another. The FRBS cost model parameters are sensitive to land use activities and socio-economic conditions. Additionally, the model parameters for COTS and IHPS are subjected to changes based on the service provider, management scheme, city bylaws, etc. Thus, in this section a set of assumptions that constrain the proposition and implementation of change are defined, enabling the development of general cost models for any specific transit route. The listed assumptions are as mentioned below.

(i) The FRBS cost model assumes a linear relationship between the bus service design demand (P_{max}), and the annual average hourly boarding (R_h) along the route (prs/h), which is estimated using Eq. (1).

$$R_h = \frac{R}{h_p + h_r} \tag{1}$$

where, R = annual ridership (prs), h_p = the number of peak hours in a year (h), and h_r = the number of off-peak hours in a year (h).

(ii) The COTS operating cost model assumes that the taxi companies follow the city's bylaw in pricing their services.

(iii) In the COTS operating cost model, the unit cost per vehicle-hour includes the unit costs for fleet operations and maintenance.

(iv) FRBS and IHPS cost models only consider operating costs for analysis, ignoring the capital and other associated costs to reduce the complexity of analytical models.

(v) The study adopts the same passenger demand (i.e. ridership) data and origin–destination (OD) matrix for analyzing the operating cost of FRBS, COTS, and IHPS services. The operating costs corresponding to lower or higher ridership values are estimated by adjusting the original OD matrix using a proper scale factor.

(vi) The FRBS cost model is designed for regular bus service along a fixed route, stop and schedule while COTS and IHPS cost models are designed for trips along a fixed route with fixed stop and flexible schedule. Further, in SFT services it is assumed that trips between stops are completed through the shortest paths.

3.3 Estimation of design demand and OD flows

The operating costs for FRBS are expressed as a function of bus fleet size. The design demand defined as the number of passengers onboard at maximum load section (MLS) is a major input parameter for estimating the required fleet size. The passenger load diagram along the bus route is plotted to identify the MLS for a given set of passengers boarding and alighting data corresponding to each stop location. Typically, the passenger boarding and alighting data recorded in an automatic passenger counting (APC) system equipped in bus fleets are collected for demand analysis. However, the bus fleets in smaller municipalities are not equipped with the APC system due to budgetary constraints. Therefore, for smaller municipalities, only passenger boarding data is collected from fare-box information. Thus, a method to derive the passenger alighting data for each bus stop using available passenger boarding data is discussed in the following sub-sections.

3.3.1 Analysis of passenger boarding data

The proposed method assumes symmetry between passenger boarding and alighting patterns at paired bus stops (i.e. closely located bus stops at opposite directions) during the morning and afternoon peak hours (Navick and Furth 2002). The bus stops along the route are grouped based on the direction of the bus service (i.e. Northbound and Southbound). A bus stop in one direction (i.e. Northbound, denoted as 1) is paired with its most closely located stop on the opposite direction (i.e. Southbound, denoted as 2). Equations (2) are used to estimate passenger alighting at stop i based on passenger boarding at its paired stop j. The equation assumes equal proportions of passenger boarding and alighting at paired stops during AM and PM peak hours.

$$\frac{PA_{\mathrm{i}}^{\mathrm{am/pm}}}{PA_{1}^{\mathrm{am/pm}}}=\frac{PB_{\mathrm{j}}^{\mathrm{pm/am}}}{PB_{2}^{\mathrm{pm/am}}} \tag{2}$$

where, i and j = indices representing paired stop locations along Northbound and Southbound direction, $PA_{\mathrm{i}}^{\mathrm{am/pm}}$ = passenger alighting at stop i during AM or PM peak hours, $PA_{1}^{\mathrm{(am/pm)}}$ = total passenger alighting for direction 1 (i.e., Northbound) during AM or PM peak hours, $PB_{\mathrm{j}}^{\mathrm{pm/am}}$ = passenger boarding at paired stop j, during PM or AM peak hours, and $PB_{2}^{\mathrm{pm/am}}$ = total passenger boarding for direction 2 (i.e., Southbound) during PM or AM peak hours.

The total passenger boarding and alighting in Eq. (2) are assumed to be approximately equal in each direction during AM or PM peak hours ($PA_{1}^{\mathrm{am/pm}} \approx PB_{1}^{\mathrm{am/pm}}$; $PA_{2}^{\mathrm{am/pm}} \approx PB_{2}^{\mathrm{am/pm}}$). However, to account for day-to-day variations in peak hour passenger boarding and alighting patterns, the annual passenger boarding data are analyzed to determine the day with maximum peak hour (e.g. AM or PM peak) passenger boarding. The day with maximum peak hour is considered as it is essential to plan the transit system for the maximum observed load or transport, which is critical for operations planning and scheduling (Vuchic 2017). Consequently, Eq. (2) can be used to estimate passenger alighting at each stop based on passenger boarding data at paired stops. The derived boarding alighting data along the bus route are used to determine the MLS and its corresponding design demand. The design demand is further used to determine the fleet size for the FRBS system.

3.3.2 Analysis of the OD matrix

The annual OD matrix is essential for estimating the operating costs of SFT services. The annual OD matrix represents the annual passenger demand flows between bus stops (i.e. trip origins and destinations). The annual OD matrix is analyzed to estimate the demand for SFT and individual trip lengths. The annual OD matrix is estimated using passenger boarding data and derived passenger alighting rates at each bus stop based on the concept of fluid analogy (Tsygalnitsky 1977). Equation (3) is defined to calculate annual passenger alighting rates based on passenger boarding data at paired stops. Similar to Eqs. (2), (3) assumes symmetry between passenger boarding and alighting demand at paired stops. Additionally, the total annual passenger boarding and alighting are assumed approximately equal in each direction (i.e. $PA_1^y \approx PB_1^y$ and $PA_2^y \approx PB_2^y$).

$$\frac{PA_i^y}{PA_1^y} = \frac{PB_j^y}{PB_2^y} \tag{3}$$

where, PA_i^y = annual passenger alighting rate at stop i, PA_1^y = annual passenger alighting rate for direction 1 (i.e., Northbound), PB_j^y = annual passenger boarding at paired stop j, and PB_2^y = annual passenger boarding for direction 2 (i.e., Southbound).

3.4 Operating cost models

3.4.1 FRBS

Typically, the annual operating cost of bus transit is expressed as a function of the fleet size, total vehicle-hours, and the total vehicle-kilometres of service as shown in Eq. (4) (Cherwony and Mundle 1980; Abbas and Abd-Allah 1999). The model parameters can be calibrated using empirical data as demonstrated in Sect. 4.

$$\left(C_R\right)_{FRBS} = \alpha_1(n) + \alpha_2\left(h_v\right) + \alpha_3(l_t) \tag{4}$$

where, $\left(C_R\right)_{FRBS}$ = annual operating cost of FRBS ($), α_1 = unit cost of purchasing a vehicle ($/veh), α_2 = unit cost of vehicle service hours ($/veh-h), α_3 = unit cost of vehicle-kilometers ($/veh-km), n = fleet size (vehicle), h_v = annual vehicle-service hours (h), and l_t = annual vehicle-kilometers of service (km).

Additionally, the annual operating cost of bus transit in Eq. (4) can be expressed as a function of the annual ridership as discussed in Sect. 4.1.

3.4.2 COTS

Typically, in transit agency contracts, the public and private transit operators define a negotiated passenger trip rate for taxi services, ensuring effective implementation of the service. The private service providers schedule passenger request to provide a ride-shared taxi service and concurrently, derive the shortest path to serve all passenger requests along a fixed bus route. Additionally, the transit operator attempts to provide service to each passenger within a specified time window of maximum wait time (MWT). The MWT is expressed as the time difference between the recording of passenger ride-request and pick-up of the passenger from the desired location. The time-window is a trade-off between operating costs and level of service. A shorter MWT results in an improved level of service but higher operating costs, and vice versa.

The fare structure of a COTS, similar to taxi is adopted to determine the operating cost per taxi trip (Turmo et al. 2018). The operating cost per taxi trip includes base fare (β_0) and fare charged as a function of delay time experienced due to congestion (β_1) and trip distance (β_2), in regard to guidelines provided in taxi bylaws. The mathematical expression for the annual operating cost of COTS is given in Eq. (5). Table 1 presents examples of taxi fare schedules indicated in taxi bylaws from several midsize Canadian municipalities.

$$\left(C_{\mathrm{R}}\right)_{\mathrm{COTS}} = \sum_{r=1}^{R}\left[\beta_0 + \beta_1\left(\frac{TC_{\mathrm{r}} - \gamma_1}{\delta_1}\right) + \beta_2\left(\frac{l_{\mathrm{r}} - \gamma_2}{\delta_2}\right)\right] \tag{5}$$

where, $\left(C_{\mathrm{R}}\right)_{\mathrm{COTS}}$ = annual operating cost of COTS (\$), r = passenger trip ID, β_0 = initial cost (base fare) (\$), β_1 = unit cost for additional congestion charge (\$), β_2 = unit cost of additional distance-related charge (\$), TC_{r} = travel time spent in congestion for trip r (h), γ_1 = threshold of travel time in congestion without additional charge (h), δ_1 = unit travel time with additional charge (h), l_{r} = distance travelled for trip r (km), γ_2 = threshold of traveled distance without additional charge (km), and δ_2 = unit traveled distance with additional charge (km)

3.4.3 IHPS

IHPS is operated by the City and its available paratransit fleet is used to deliver a scheduled, ride-shared service with per-passenger requests. The proposed IHPS transports passengers from defined origins to defined destinations along the fixed bus route as discussed in Sect. 1; whereas a conventional IHPS is designed to provide door-to-door service. Typically, the operation cost model of IHPS follows the structure similar to a conventional bus (FRBS) service, as the paratransit system is completely operated and administered by the public transit agency.

However, the study realizes the inadequacy and difficulty in obtaining detailed information such as the cost-per-vehicle service hour, and the cost-per-vehicle traveled distance for a paratransit operation. Thus, the present study proposes to express IHPS operating costs as a function of vehicle service hour (TS_{r}) and deadheading time (TD_{r}) as given in Eq. (6). Deadheading time, in this case, refers to the periods when there are no passengers on board for a specific trip. A detailed description and the set of equations to obtain the deadheading time is discussed in Sect. 4.4. Public transportation agencies generally estimate the unit cost per vehicle service hour for their paratransit services as part of their financial analysis process. The parameter cost per vehicle service hour (ρ) primarily includes hourly wage and benefits of staff and hence, commonly multiplied to service hour and dead-heading time.

$$\left(C_{\mathrm{R}}\right)_{\mathrm{IHPS}} = \rho \times \sum_{r=1}^{R}(T_{\mathrm{r}}) = \rho \times \sum_{r=1}^{R}(TS_{\mathrm{r}} + TD_{\mathrm{r}}) = \rho \times \sum_{r=1}^{R}\left(\frac{l_{\mathrm{r}}}{s_{\mathrm{r}}} + TD_{\mathrm{r}}\right) \tag{6}$$

where, $\left(C_{\mathrm{R}}\right)_{\mathrm{IHPS}}$ = annual operating cost of IHPS (\$), ρ = cost per vehicle service hour (\$/h), TS_{r} = vehicle service hour for trip r, TD_{r} = deadheading time trip r, and s_{r} = operating speed for trip r (km/h).

Table 1 Taxi fare schedule in selected medium size Canadian cities

Municipalities	Base Fare	Time-related cost	Travel distance-related cost	References
Stratford	$8 for 1-2 riders and $9 for 3 and more	$30/h for waiting time	$1.40/km after first 5 km	Taxi Bylaw no. 3-2004; Stratford Police Service Board, City of Stratford
Peterborough	$4 for the first 55 m	$0.25 for each 28 s or $32.50/h	$0.25 after first 55 m for each additional 111 m	Bylaw No. 112-2017; Peterborough Police Services Board
Barrie	$3.25 for the first 100 m	$30/h for waiting time	$0.25 after first 100 m for each additional 100 m	Transportation Industry Bylaw 2006-265, City of Barrie
Saskatoon	$3.75 for the first 130 m	$0.25 for each additional 35 s	$0.25 after first 130 m for each 130 m	Bylaw No.9070; The Taxi Bylaw, 2014; City of Saskatoon
Regina	$4 for the first 120 m	$0.25 after first 5 min for each additional 25 s	$0.25 after first 120 m for each additional 138 m	The Taxi Bylaw No. 9653; City of Regina

4 Model application

4.1 Study area and data

The application of the proposed operating cost models and the analysis method is demonstrated using a low demand bus route in Regina, a medium size city in Western Canada. Figure 1 illustrates and compares the cost performance of bus transit systems in Regina to Canadian municipalities with comparable population density. Canadian Transit Fact Book 2015 Operating Data (CUTA 2015) was used to estimate revenue to cost ratio (R/C), and average passenger-per-vehicle hours (P/H) as performance indicators for traditional bus services. The city of Regina is one of the municipalities with both *R*/*C* and *P*/*H* slightly lower than the average values.

Figure 2 presents *R*/*C* and *P*/*H* trends for all bus routes in the city of Regina. The results indicate similar trends for *R*/*C* and *P*/*H* ratios as both indicate the economic performance of bus transit services from different angles. Figure 2 suggests that bus routes 14, 15, and 16 with very low annual ridership, have the lowest economic performance in Regina.

The proposed methodology is applied to a low-demand bus route, Route 14 in Regina as a case study. The route is located in the southeast of Regina, serving a mixed land-use area as it passes through commercial, institutional, open space/recreational, and residential areas as shown in Fig. 3. The route is 9.84 km long and characterized with an annual ridership of 9954 passengers and 26 stops in both

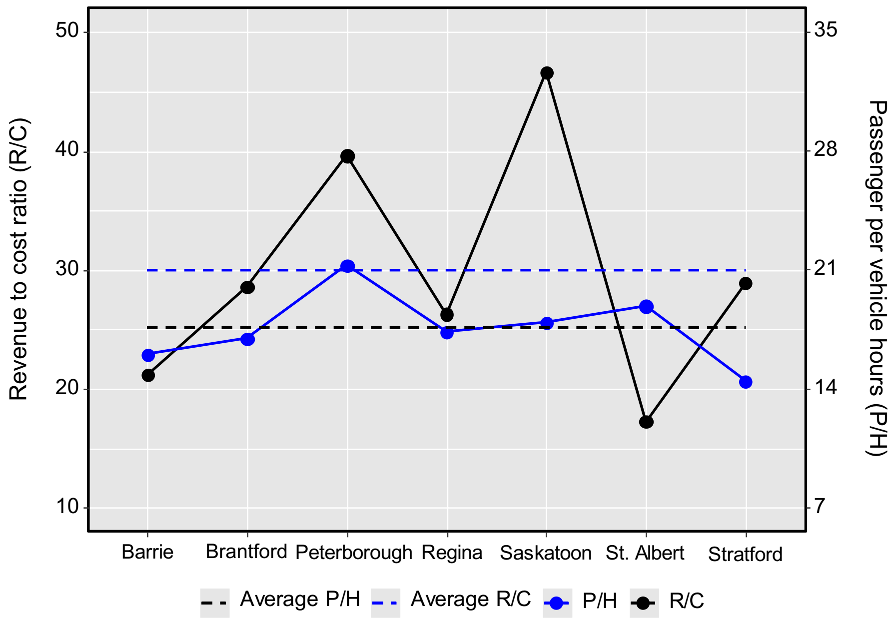

Fig. 1 Revenue to cost ratio (*R*/*C*) and average passenger per vehicle hours (*P*/*H*) for selected bus transit systems in medium size Canadian municipalities

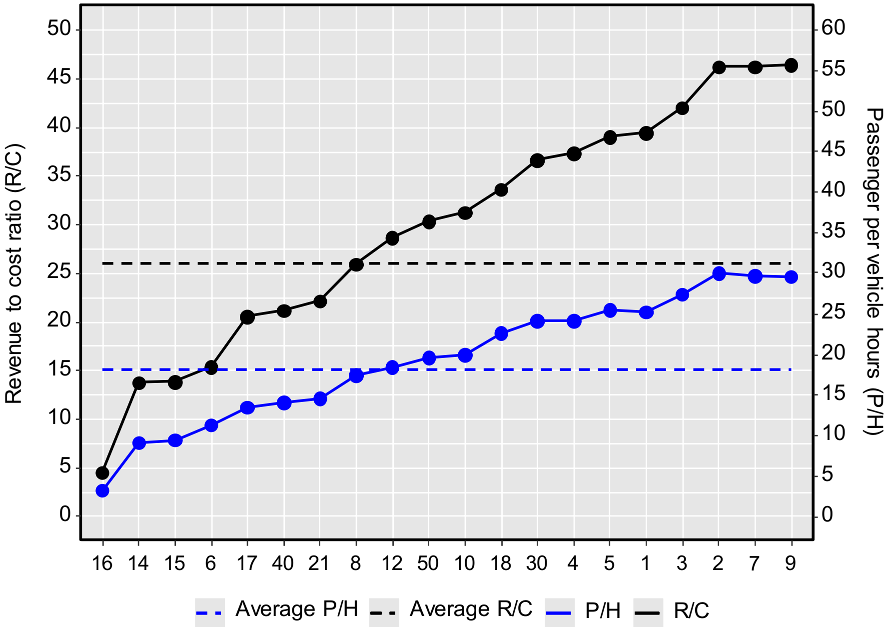

Fig. 2 Economic performance indicators for Regina bus routes

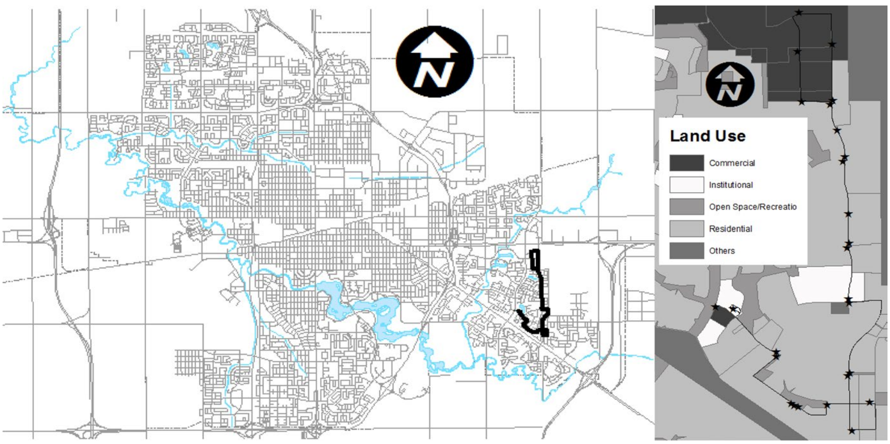

Fig. 3 Bus route 14 in Regina

directions. Considering low ridership trends, the provision of SFT service is a viable option to improve the economic efficiency of route 14.

The proposed analysis method will enable transit planners to quantify and compare the operating costs of regular and semi-flexible transit services as a function of annual ridership. The data required for operating cost model development and calibration are collected in 2015 from Regina Transit Services for all bus routes in Regina. The data-set includes hourly, weekly, and monthly passenger boarding data at bus stops, operating cost data, for bus routes and paratransit services, vehicle service hours for bus routes; and fleet size in peak and off-peak hours for bus routes.

4.2 Calibration of FRBS operating cost model

The FRBS operating cost model indicated in Eq. (4) is calibrated using Regina's bus route data in 2015. Table 2 shows the Pearson correlation coefficients for FRBS model parameters. The results indicate a significant correlation between, fleet size (n), vehicle service hours (h_v), and the vehicle traveled distance (l_t). Thus, independent parameters are examined one-by-one for model development.

The cost model development considering each parameter suggested that FRBS operating cost can be modeled with high accuracy (adjusted $R^2=0.95$) as a function of vehicle service hours (h_v). Equation (7) shows the regression model developed for FRBS operating cost. The model parameters are statistically significant ($p=0.05$).

$$\left(C_{\mathrm{R}}\right)_{FRBS} = 91.80 \times h_{\mathrm{v}} \tag{7}$$

Figure 4 compares estimated and actual bus operating costs for all 20 bus routes in Regina using the developed model presented in Eq. (7).

Additionally, the total annual operating cost equation of FRBS (i.e., Eq. 7) is expressed as a function of annual bus ridership or annual passenger demand as illustrated using Eqs. (8) to (13). The vehicle service hours (h_v) in Eq. (7) can be rewritten as the sum of total service hours during peak and off-peak hours:

$$h_{\mathrm{v}} = v_{\mathrm{p}} \times h_{\mathrm{p}} + v_{\mathrm{r}} \times h_{\mathrm{r}} \tag{8}$$

where, v_p = number of operating vehicles in peak hours, and v_r = number of operating vehicles in off-peak hours.

The number of operating vehicles in peak hours, v_p in Eq. (8) represents the required fleet size during peak hours which can be estimated using Eq. (9):

$$v_{\mathrm{p}} = \frac{L \times P_{\max}}{s \times C \times LF} \tag{9}$$

where, L = cycle length of bus transit along the route (h), $P_{\max}$ = design demand (prs/h), s = average operating speed (km/h), C = capacity of the bus (prs/veh), and LF = bus load factor.

Table 2 Correlation analysis for FRBS cost model parameters

	$\left(C_{\mathrm{R}}\right)_{\mathrm{FRBS}}$	n	h_{v}	l_{t}
$\left(C_{\mathrm{R}}\right)_{\mathrm{FRBS}}$	1			
n	0.8502	1		
h_{v}	0.9997	0.8506	1	
l_{t}	0.9774	0.7826	0.9773	1

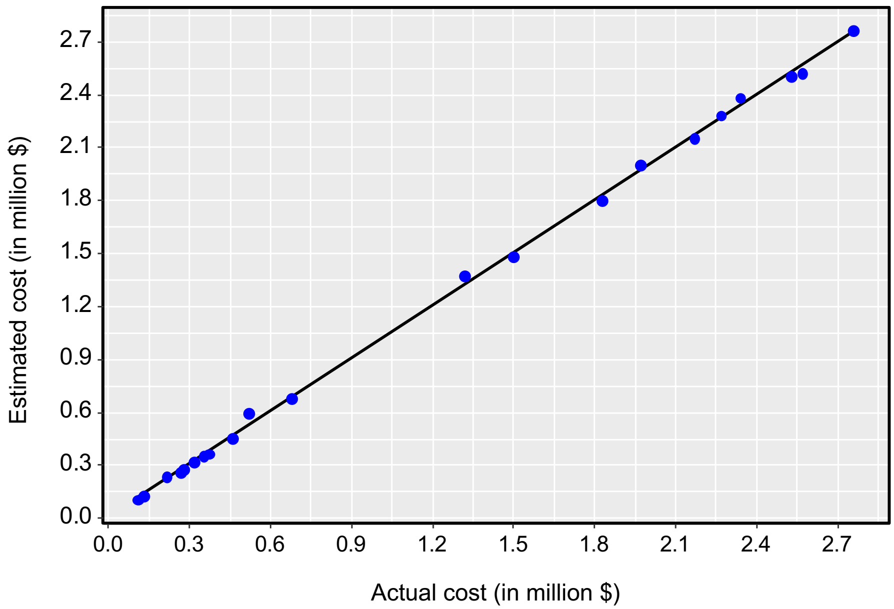

Fig. 4 Demonstration of the performance of FRBS operating cost model

Further, assuming a linear relationship between design demand ($P_{\max}$) and average hourly passenger boarding (R_{h}), and considering Eq. (1), Eq. (10) is expressed as:

$$\gamma = \frac{P_{\max}}{R_{\mathrm{h}}} = \frac{P_{\max} \times (h_{\mathrm{p}} + h_{\mathrm{r}})}{R} \tag{10}$$

where, γ = ratio of design demand to average hourly passenger boarding.

Thus, by solving Eq. (10) for design demand ($P_{\max}$), Eq. (11) is expressed as:

$$P_{\max} = \frac{\gamma \times R}{h_{\mathrm{p}} + h_{\mathrm{r}}} \tag{11}$$

Consequently, v_{p} is derived and represented through Eq. (12) by combining Eqs. (9) and (11):

$$v_{\mathrm{p}} = \left[\frac{L \times \gamma \times R}{s \times C \times LF \times \left(h_{\mathrm{p}} + h_{\mathrm{r}} \right)} \right]^{+} \tag{12}$$

Finally, the annual operating cost of FRBS expressed using Eq. (13) is derived by combining Eqs. (7), (8), and (12):

$$(C_{\mathrm{R}})_{\mathrm{FRBS}} = 91.80 \times \left(\left[\frac{L \times \gamma \times R}{s \times C \times LF \times (h_{\mathrm{p}} + h_{\mathrm{r}})} \right]^{+} \times h_{\mathrm{p}} + v_{\mathrm{r}} \times h_{\mathrm{r}} \right) \tag{13}$$

The values of other dependent parameters in Eq. (13) are assumed or estimated by analyzing the data provided by the City of Regina, as shown in Table 3. The bus design demand (P_{max}) at MLS and the ratio of design demand to average hourly passenger boarding (γ) for bus route 14 are estimated based on the methodology described in Sect. 3.3 using 2015 bus ridership data. The load factor (LF) is defined as the ratio of design load to the line capacity offered. Typically, a uniform distribution of passenger volume along the bus route suggests a lower value of LF and a non-uniform distribution of passenger demand suggests a higher value of LF (Vuchic 2017). The passenger volume is concentrated on a short section along the route resulting in a higher value of LF. Bus route 14, is a low demand route with a non-uniform distribution of passengers along the route; thus, a higher value of load factor is considered.

4.3 Calibration of COTS operating cost model

The calibration of the operation cost model for COTS defined in Eq. (5) is performed in this section. The bus route 14 serves as a subdivision with very low traffic volumes and uncongested roads; hence, experiencing minimum or no congestion. Thus, the second term in Eq. (5) representing additional charges for the time spent in congestion is ignored in the analysis and Eq. (16) represents the revised form of Eq. (5). The third term in Eq. (5) represents the distance-based taxi fare component. The average trip distance (τ) in Eq. (14) is estimated based on the annual passenger OD matrix and the shortest paths between all the stops. Bus ridership data in 2015 was analyzed based on the methodology described in Sect. 3.3.2 to estimate the annual OD matrix.

$$\tau = \frac{PD\mathrm{s}}{R} \tag{14}$$

where, τ = average travel distance per passenger (km), and PDs = total passenger travelled distance (km).

The total passenger travelled distance (PDs) is calculated by summing the product of OD flows (F_{ij}) and the shortest paths (D_{ij}) from stop i to j for k number of stops.

Table 3 Values of the parameters used in Eq. (13)

Parameter	L	γ	s	C	LF	h_{p}	v_{r}	h_{r}
Value	9.84 km	1.219	19.68 km/h	67[a]	0.9[a]	251 h/yr	1	1096.83 h/year

[a]Assumed values

$$\mathrm{PD_s} = \sum_{i=1}^{k}\sum_{j=1}^{k}(F_{\mathrm{ij}} \times D_{\mathrm{ij}}) \tag{15}$$

where, i and j = indices representing trip origin and destination, respectively, k = number of stops along the route, $\mathrm{F_{ij}}$ = number of passengers travelling from stop i to stop j, and $\mathrm{D_{ij}}$ = distance between stop i to stop j.

Further, given m as the average number of passengers on board for each taxi trip, Eq. (5) can be written as:

$$\left(C_{\mathrm{R}}\right)_{\mathrm{COTS}} \approx \frac{R}{m}\left[\beta_0 + \beta_2\left(\frac{\tau - \gamma_2}{\delta_2}\right)\right] \tag{16}$$

The estimated and assumed model parameters adopted for calibration are shown in Table 4.

4.4 Calibration of IHPS operating cost model

The operating cost model for IHPS defined in Eq. (6) is simplified by introducing τ and m in the cost equation as shown in Eq. (17).

$$\left(C_R\right)_{\mathrm{IHPS}} \approx \rho \times \frac{R}{m} \times \left(\frac{\tau}{s} + f \times TD_{\mathrm{max}}\right) \tag{17}$$

where, TD_{max} = average of maximum deadheading times for all trips (h).

The values of ρ and s are set to \$63.50/h and 19.68 km/h based on the data provided by the City of Regina. The service time in Eq. (6) is defined as a function of average travel distance per passenger and average operating speed. The deadheading time is defined as a percentage ($0 \le f \le 1$) of TD_{max} which is the average of maximum deadheading time for all trips. The average maximum deadheading time TD_{max} can be estimated using Eq. (18) considering each trip from a stop i to j with L_{i} and L_{j} as the distance from the dispatch center to stops i and j, respectively, and F_{ij} as the OD flow from i to j.

$$TD_{\mathrm{max}} = \frac{\sum_{i=1}^{k}\sum_{j=1}^{k}[F_{\mathrm{ij}} \times (L_{\mathrm{i}} + L_{\mathrm{j}})]}{s \times R} \tag{18}$$

where, L_{i} and L_{j} = distance from the dispatch center to stops i and j, respectively.

Table 4 Values of the parameters used in calibration of Eq. (16)

Parameter	β_0	β_2	τ	γ_2	δ_2
Value	\$4/prs	\$0.25/m	1.425 km	0.120 km	0.138

4.5 Comparisons of FRBS, COTS, and IHPS operating costs as function of annual ridership

The total operating costs (C_R) are modeled as a function of annual ridership (R) for FRBS, COTS, and IHPS in Eqs. (13), (16) and (17), respectively, making it possible to analyze and compare the operating costs. Figure 5 presents the variations of the operating cost models as a function of annual ridership for FRBS, COTS, and IHPS services for bus route 14 in Regina. Line 1 represents the FRBS cost model defined in Eq. (13). The results indicate that a single bus can sufficiently serve both peak and off-peak hours on route 14 until the annual ridership reaches 132,573 passengers per year, at which an additional bus will be required to serve peak hours. Line 2 and Line 3 are drawn based on Eq. (17). Line 2 represents the worst scenario for IHPS assuming $m = 2$ and $f = 50\%$, indicating each paratransit vehicle serves only two passengers on average per each service, and the deadheading time is 50% of TD_{max}. Line 3 represents the best scenario for IHPS operation assuming every paratransit vehicle has an average occupancy of 5 passengers while the deadheading time is just 20% of TD_{max}. Equation (16) is used to produce Line 4 and Line 5 for COTS operating cost model. Line 4 represents the worst scenario for COTS operations and indicates every taxi serves only one passenger at a time. Line 5 represents the best scenario (highest efficiency) assuming each taxi is always fully occupied ($m = 3$) between origin and destination stops. Thus, the results indicate that the average number of passengers per vehicle (m) and deadheading time (for IHPS) is essential in determining the operating cost of SFT services. Although, the worst- and best-case scenarios identify the feasible ranges for each SFT service cost model based

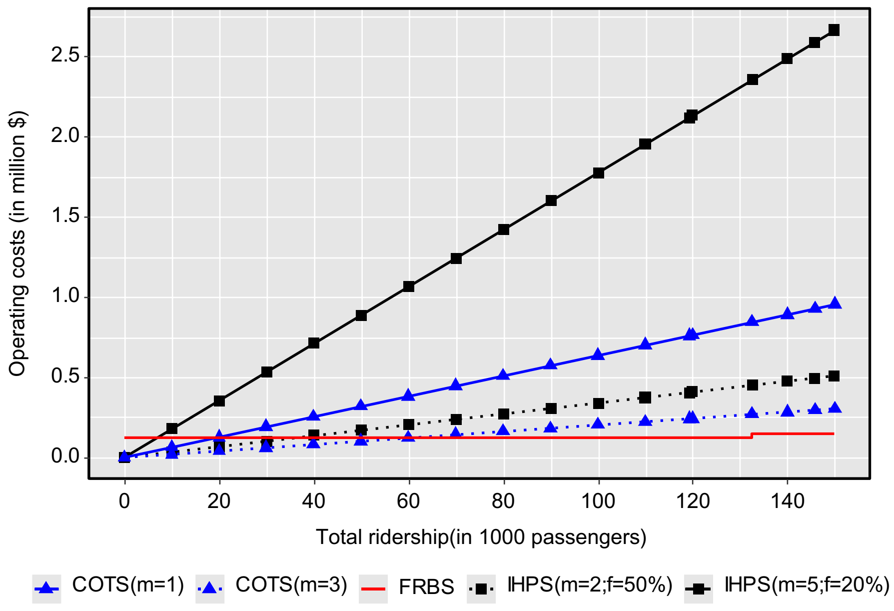

Fig. 5 The relationship between operating costs and annual ridership for FRBS, COTS, and IHPS

on different values of m ($1 \leq m \leq 10$ for IHPS; $1 \leq m \leq 3$ for COTS). However, it is imperative to note that the best and worst scenarios are not realistic. Table 5 provides some of the preliminary observations based on the results presented in Fig. 5 (inequalities compare the economic performance of each service).

The analysis results support some definite observations and indicate that the critical values of annual ridership for switching from one service to another can be determined based on some simple assumptions. Additionally, performing a more detailed analysis of the economic evaluation of different options is possible. For instance, corresponding to annual ridership value for route 14, a minimum required average occupancy rate that would enable cost savings and better economic performance on switching from FRBS to COTS or IHPS can be determined. A similar analysis and representation as in Fig. 5 can be illustrated for any other bus route based on more realistic values for the average number of passengers per vehicle (m) and deadheading time. The analysis results enable transit planners to compare the efficiency of SFT and FRBS services in low demand areas.

Further, a sensitivity analysis of the operating cost model is performed to identify the variability in cost corresponding to changes in the input parameters as shown in Fig. 6. Figure 6 indicates the impact of changing the operating speed (s) of FRBS and IHPS by ± 10% (indicated by 0.9 s and 1.1 s) on the operating costs. A change in average operating speed affects the FRBS cost model as the corresponding required fleet size changes. From Fig. 6 it is apparent that the addition of the second bus is required earlier if operating speed is reduced, and vice versa. On the other hand, a lower operating speed will result in higher operating costs for IHPS and vice versa. The corresponding demand threshold points of operating cost models can be determined accordingly to compare the performance of each service based on the best and worst operating scenarios.

5 Conclusions

The study develops analytical models to evaluate and compare the operating costs of regular bus and SFT services. The proposed SFT service is based on two types of service delivery systems, i.e. Contract-Out Taxi Service (COTS), and

Table 5 Comparison of the economic performance of bus and the SFT services as function of the annual ridership (bus route 14)

(a) Worst scenarios for SFT services		(b) Best scenarios for SFT services	
Annual ridership	Economic performance	Annual ridership	Economic performance
$1 \leq R < 6,958$	$COTS > IHPS > FRBS$	$1 \leq R < 33,257$	$IHPS > COTS > FRBS$
$R = 6,958$	$COTS > IHPS = FRBS$	$R = 33,257$	$IHPS > COTS = FRBS$
$6,958 < R < 19,485$	$COTS > FRBS > IHPS$	$33,257 < R < 61,393$	$IHPS > FRBS > COTS$
$R = 19,485$	$COTS = FRBS > IHPS$	$R = 61,393$	$IHPS = FRBS > COTS$
$R > 19,485$	$FRBS > COTS > IHPS$	$R > 61,393$	$FRBS > IHPS > COTS$

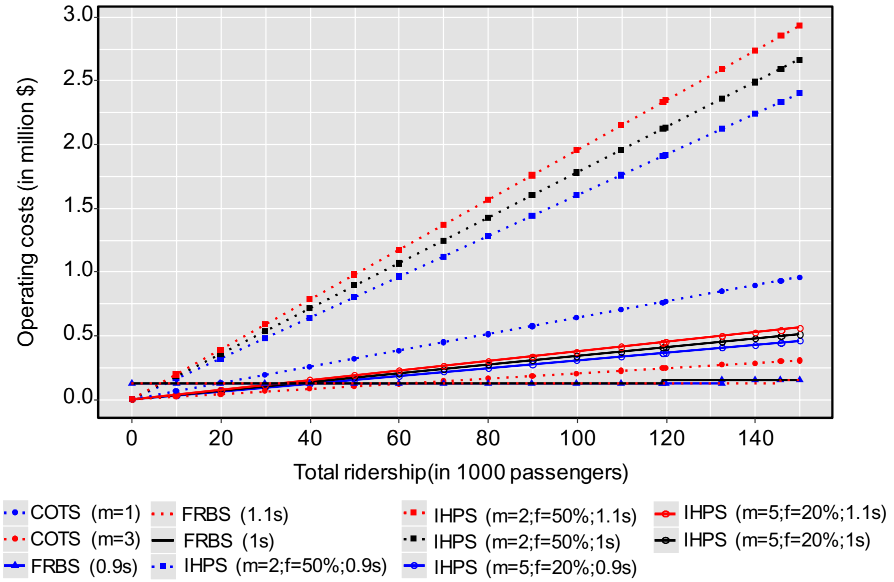

Fig. 6 Sensitivity analysis of operating cost with respect to the average speed

In-House Paratransit Service (IHPS). The SFT service is delivered along the fixed bus route and a limited number of fixed stops based on a flexible schedule to meet passenger requests, intended to serve the general public. Appropriate cost models are developed based on simple assumptions for each service type to describe the operating costs as a function of annual ridership. The proposed models enable determining the critical values of annual ridership to switch from FRBS to COTS or IHPS, and vice versa. The vehicle service hour is found to be the most significant independent parameter for modeling FRBS operating costs when compared to fleet size and total vehicle-kilometers. The cost model for COTS included basic, time-dependent, and distance-based fare components. The IHPS cost model has developed a function of vehicle service hour and deadheading time. Some applications of the proposed models are demonstrated using a low demand bus route in Regina. The analysis results for SFT services indicate that operating costs are strongly related to the average vehicle occupancy rate and deadheading time. The proposed models enable transit agencies to estimate and compare the operating costs of the bus system with SFT services to evaluate the feasibility of replacing regular bus services with SFT services in low demand areas. The proposed analysis method and models are simple, flexible, and highly transferrable as they can be easily calibrated using locally available transit data. The analytical models developed in this study can be used either at the planning level before implementing a new fixed bus route or for operational planning of existing low demand bus routes. Thus, the proposed analysis method can be applied to establish planning and operations policies for FRBS and SFT services in areas with low demand for public transportation.

Further, the proposed SFT system promotes travel time savings by offering vehicles the flexibility to cover a section of the entire route based on the spatial distribution of passenger demand; unlike buses, which cover the entire route in each trip. However, the proposed system is not efficient in providing accessible services and requires transit operators to be equipped with specialized software and highly skilled personnel to manage the passenger requests and schedule the dispatch of a vehicle.

The proposed operating cost models are based on several assumptions and need further refinement and validation to generalize its application. The assumption of a linear relationship between the bus design demand and the average hourly ridership can be evaluated using historical bus ridership data. The present study derived passenger alighting data using passenger boarding data by assuming a symmetry between passenger boarding and alighting ratios, which needs validation using field surveys. Further, the best and worst-case scenarios identified for COTS and IHPS cost models are estimated based on extreme values for vehicle occupancy rate and deadheading time. However, the values of these parameters could be estimated based on more realistic assumptions. In this study the annual operating cost was modeled as a function of annual ridership. The scope of the study could be broadened by investigating the variations of operating cost per passenger as function of hourly demand considering that the demand for public transportation is changing dynamically as a result of varying daily activity patterns. Finally, the present study considers only the operating costs as the main decision criteria to switch from FRBS to SFT services. However, the inclusion of other important criteria in cost models such as level of service and user costs including access and in-vehicle time is essential, which will be considered in the future extensions of this research.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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