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A METHODOLOGY FOR FEASIBILITY ANALYSIS OF DEMAND-RESPONSIVE TRANSIT SERVICES

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Abstract: Under low demand conditions, bus transit operators have to pay a high cost per passenger to maintain desired level of service. Therefore, Demand-Responsive Transit (DRT) becomes an alternative option for transit agencies. Unlike regular transit services which run on fixed routes and schedules, DRT operates per user requests on variable routes or schedules to reduce operating costs while providing acceptable service level. DRT service is preferred when demand for public transportation is low. However, as the demand or bus ridership increases, a regular bus service is more efficient. Determining the critical demand levels for switching from a regular bus service to DRT is essential for transit operators. A methodology is proposed to evaluate and compare the oprerational costs of offering regular and demand responsive bus services. The proposed cost model for regular bus service has three independent parametrs i.e. fleet size, vehicle service hours, and vehicle traveled distance. Model parameters were estimted using the City of Regina's bus transit data. Two DRT service models were considered: 1) Contract-out Taxi Service (COTS) and, 2) In-house Paratransit Service (IHPS). The proposed cost models can be used to estimate expected operational costs of regular and demand responsive bus services as function of demand. A low demand bus route in Regina was used as a case study to demonstrate the application of the proposed methodology.

1 INTRODUCTION

Low ridership is a significant challenge for bus transit operators in small to medium municipalities in Canada, especially for newly developed areas, residential subdivisions, and communities with specific social-economic characteristics. Low ridership results in lower revenues for transit operators. Therefore, additional costs should be covered either by increasing the fares, or reducing the service frequency, which can affect the level of service and customer satisfaction. On the other hand, eliminating bus services in low demand areas is not an option because municipalities are required to provide public transportation services to their citizens as part of essential amenities to maintain acceptable living standards in urban areas. Thus, determining feasible and efficient public transit options for low demand areas is critical for bus transit agencies. Demand-Responsive Transit (DRT) is a viable option for transit agencies in low ridership situation. Unlike regular transit services which run on fixed routes and schedules, DRT operates per user requests on flexible routes or schedules to reduce operating costs and ideally maintain the same, or even better levels of service. It is anticipated that DRT service is preferred when demand for public transportation is low. However, as the demand increases, a regular bus service is more efficient. Determining the critical demand levels for switching from a regular bus service to DRT (and vice versa) is essential for transit operators. In this paper a methodology is proposed to evaluate and compare the oprerational costs of offering regular and demand responsive bus services. Contract-Out Taxi Service (COTS), and In-House Paratransit Service (IHPS) are considered as feasile DRT services to replace

Fixed-Route Bus Service (FRBS) in low demand conditions. Analytical models are developed to estimate the operating costs of regular and proposed demand responsive transit services. A low demand bus route in the City of Regina is used as an example to demonstrate model applications. The rest of the paper is organized as below. After a brief review of the existing literature, the cost models for FRBS, COTS, and IHPS services are described in Section 3. Section 4 describes a case study to demonstrate the aplications of the proposed analyese methods. Sensitivity analyses are carried out in Section 5 to evalute the cost models' responses to variations in input variables. The article ends with conclusions in Section 6 which provides a brief summary and recommendations for future research.

2 LITERATURE REVIEW

DRT is describes as a flexible route and/or schedule, shared ride, per user requests transportation services between public fix-route bus services and single-hired taxi services (KFH Group 2008). A study conducted by Rufolo (1995) in Poland concluded that DRT is suitable for low demand neighbourhoods compared to fixed route bus service, and it is preferable to use contract-out service rather than in-house management in terms of cost-effectiveness of DRT services. A survey conducted by Pamler et al. (2007) including 67 large U.S. transit agencies investigated the impact of implementation of new technologies for DRT across the country. Their study concluded that implementation of new technologies and practices can improve the productivity and reduce the costs of DRT services. Laws et al (2009) investigated publicly funded DRT schemes in England and Wales, and concluded that it is important to invest sufficient time in the design phase, and the system should be simple and meet the needs. Case studies from New Zealand and Australia indicated that the majority of efficacious DRT services are provided to commuters, schoolchildren, and shoppers. Moreover, many-to-one operation was found to be more successful than many-to-many services. It was also found that limited-stops services are more successful than door-to-door services (Scott, 2010).There are limited numbers of researches on the comparison of regular bus transit service and DRT. Diana et al. (2009) compared the performance of a competing fixed route transit and a DRT service in terms of traveled distance by these services while ensuring a comparable service to the same set of customers. They found that DRT provided higher level of service than fixed route transit under low demand scenarios. Li and Quadrifoglio (2010) proposed an analytical model to compare fixed route transit and DRT which could be used to determine when to switch from one to another during the day. Edwards and Watkins (2013) used a dataset including 10% of Metropolitan Atlanta Rapid Transit Authority passenger surveys, and developed a methodology to compare the performance of fixed route bus and DRT over a wide variety of streets and transit service layouts. Their methodology could be used by transit planners to determine whether DRT should be used instead of Fixed Route Transit to save costs and improve customer satisfaction. The review of the existing literature confirms that the existing methodologies for evaluating DRT are:

1. Mainly theoretical and based on simplified road networks, and passenger survey data,
2. Generally based on ideal scenarios, and
3. Often case specific and valid under specific circumstances.

This research aims to develop a general quantitative approach for comparing regular and alternative DRT services in terms of their operating costs. Furthermore, the proposed analysis methods in this research enable evaluation of the operating costs considering variations in future demand, OD flows, and other input parameters which can occur due to changes in socio-economic factors, land use patterns, and local policies. Therefore, the results of this study can be used by transit planners as a decision support tool to determine the conditions for switch between regular and demand responsive transit services in low demand conditions.

3 METHODOLOGY

In this study two DRT services are considered i.e. COTS and IHPS. In COTS DRT scheme, the transit agency contracts out the public transportation services for low demand neighbourhoods to a private taxi service provider who will be responsible for serving the demand for public transportation in designated zones based on a mutually agreed pricing scheme. IHPS based DRT relies on the existing paratransit service and fleet to serve low demand areas. In this scheme paratransit vehicles are deployed upon requests for ride to pick passengers from designated locations close to their actual trip origin. To compare and assess FRBS, COTS, and IHPS, the DRT services discussed in this paper are featured with i) fixed pick-up and drop-off locations (same as fixed bus stops), and ii) flexible schedules and routes. The number of passengers boarding at various bus stops is treated as demand or expected ridership for DRT as well. DRT services are assumed to operate per user requests. It is assumed that DRT users contact a call centre to arrange their trip by providing the information regarding their trip origin, destination, and preferred departure time. Pick-up and drop-off time and locations will be determined by the operator based on the user's preferred origin, destination, and departure time. A DRT service will be deployed as soon as adequate requests for service is received or the maximum wait time is reached. The users will be picked-up and dropped-off at predefined locations which are the bus stops nearest to their preferred trip origins and destinations, respectively. The DRT service will operate through the shortest paths between trip origins and destinations and may serve multiple pick up and drop off locations in a single trip.

3.1 Cost Model Assumptions

Operating cost models are developed for FRBS, COTS, and IHPS to describe the operating costs (dependent variable) as function of ridership and other service specific parameters (independent variables). Operating cost models enable detailed comparison of FRBS with COTS and IHPS to determine the ridership thresholds to switch from one service to another. FRBS cost model parameters may vary depending on land use activities and social economic conditions. Model parameters for COTS and IHPS may also vary depending on service provider, management scheme, city bylaws, etc. Hence, in this study the following assumptions have been made to enable development of general cost models for any specific transit route:

1. For FRBS, a linear relationship is assumed between the bus service design demand (P_{max}), and the annual average hourly boarding (R_h) along the route.

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

Model parameters are defined in Table 1.

2. For COTS, the taxi companies follow the city's taxi bylaw (e.g. City of Regina) in pricing theirs services.
3. For IHPS, the unit cost per vehicle-hour (e.g. provided by the City of Regina), represents the unit costs for fleet maintenance and operations.
4. For FRBS and IHPS, only operating costs are considered. Capital and/or other costs are not considered in this analysis.
5. It is assumed that passenger demand (i.e. ridership) and origin-destination (OD) matrix are the same for FRBS, COTS, and IHPS services. To estimate the operating costs corresponding to lower or higher ridership values, the original OD matrix is rescaled, respectively.
6. For FRBS, a fixed route is considered with predefined stops. Similar predefined stops are considered for COTS and IHPS. However, it is assumed that the trips between stops are completed through the shortest paths.

3.2 Estimation of Design Demand and OD Flows

The operating costs for FRBS is directly related to bus fleet size. The design demand is one of the main input parameters for estimating the required fleet size for FRBS, which refers to the number of passengers onboard at Maximum Load Section (MLS). Passenger load diagram can be used to identify the MLS and the corresponding design demand if passenger boarding and alighting is known at each stop along the bus route. In this study, it is assumed that only passenger boarding data is available at each bus stop. Thus, a methodology is proposed to estimate passenger alighting at each bus stop using available passenger boarding data. The proposed method assumes that there is a 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). For a bus route with stops distributed in each direction (e.g. north bound and southbound), the stops are grouped based on the direction of the bus route. Each stop in one direction (e.g. 1 for northbound) is paired with its most closely located stop on the opposite direction (e.g. 2 for southbound). Equations [2] is used to estimate passenger alighting at stop i based on passenger boarding at its paired stop j. In this equations it is assumed that the proportions of passenger boarding and alighting are equal for paired stops during AM and PM peak hours.

Table 1: Parameters, definitions, and units

Variables	Definition	Unit
α_1	unit cost of number of vehicles	$/veh/yr
α_2	unit cost of vehicle service hours	$/hr
α_3	unit cost of vehicle traveled distance	$/km
n	number of vehicles	veh
l_t	vehicle traveled distance	km/yr
h_v	number of vehicle service hours	hr/yr
v_p	number of operating vehicles in peak hours	veh
h_p	number of peak hours	hr/yr
v_r	number of vehicles in off-peak hours	veh
h_r	number of off-peak hours	hr/yr
γ	ratio of design demand to average hourly passenger boarding	-
L	cycle Length	km
R	annual ridership	prs/yr
s	average operating speed	km/hr
C	bus capacity	prs/veh
LF	bus loading factor	
β_0	initial cost (base fare)	$
β_1	unit cost for additional congestion charge	$
β_2	unit cost of additional distance related charge	$/hr
TC_r	travel time in congestion from location (i) to (j) for trip r	hr
γ_1	threshold of travel time in congestion without additional charge	hr
δ_1	unit travel time with additional charge	hr
L_r	distance from location (i) to (j) for trip r	km
γ_2	threshold of traveled distance without additional charge	km
δ_2	unit travelled distance with additional charge	km
τ	average travel distance per passenger	km
R	annual ridership	prs/yr
m	average passengers on board for each service	prs
ρ	cost per vehicle service hour	$/hr
T_r	total vehicle hours for trip r	hr
s_r	operating speed for trip r	km/hr
Ts_r	vehicle service hour for trip r	hr
l_r	trip distance from location (i) to (j) for trip r	km
Td_r	dead heading time trip r	hr
Td_{max}	average of maximum dead heading times for all trips	hr

[2] $$\frac{PA_i^{am/pm}}{PA_1^{am/pm}} = \frac{PB_j^{pm/am}}{PB_2^{pm/am}}$$

Where, $PA_i^{am/pm}$ = passenger alighting at stop (i) during AM or PM peak hours, $PA_1^{am/pm}$ = total passenger alighting for direction 1 (e.g. northbound) during AM or PM peak hours, $PB_j^{pm/am}$ = passenger boarding at paired stop (j), during PM or AM peak hours and $PB_2^{pm/am}$ = total passenger boarding for direction 2 (e.g. southbound) during PM or AM peak hours. In equation [2] the total passenger boarding and alighting are assumed to be equal in each direction during AM or PM peak hours ($PA_1^{am/pm} = PB_1^{am/pm}$; $PA_2^{am/pm} = PB_2^{am/pm}$). Considering day-to-day variations in peak hour passenger boarding and alighting patterns, the annual passenger boarding data should be analyzed to determine the day with maximum peak hour (e.g. AM or PM peak) passenger boarding. Consequently, equation [2] can be used to determine the MLS and its corresponding design demand. Another important input which is mainly required for estimating the operating costs of DRT services considered in this study is the annual OD matrix. The annual OD matrix represents annual passenger exchange rates between bus stops (i.e. trip origins and destinations). The annual OD matrix is needed for estimating important parameters such as demand for DRT and individual trip lengths. To estimate the annual OD matrix, first equation [3] is used to calculate annual passenger alighting rates at each bus stop based on passenger boarding data. Similar to equation [2], equation [3] is based on the assumption of symmetry between passenger boarding and alighting at paired stops. Consequently, the annual OD matrix is computed based on passenger boarding data and estimated passenger alighting rates using a methodology proposed by Tsygalnitsky (1977) which is based on fluid analogy.

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

Where, PA_i^y = annual passenger alighting rate at stop (i), PA_1^y = annual passenger alighting rate for direction 1 (e.g. northbound), PB_j^y = annual passenger boarding at paired stop (j), and PB_2^y = annual passenger boarding for direction 2 (e.g. southbound).

In equation [3] it is assumed that the total annual passenger boarding and alighting are approximately equal in each direction (i.e. $PA_1^y = PB_1^y$ and $PA_2^y = PB_2^y$).

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3.3 Operating Cost Models

3.3.1 FRBS

A variety of operating cost models have been proposed for FRBS in the literature (e.g. Cherwony and Mundle, 1980; Abbas and Abd-Allah, 1998). For a given bus route, there is a consensus that annual FRBS operating costs (C_R) are mainly function of the fleet size (n), total vehicle-hours (h_v), and the total vehicle-kilometres (l_t) of service, as shown in equation [4]. Model parameters can be calibrated using empirical data as demonstrated in section 4.

[4] $$C_R = \alpha_1(n) + \alpha_2(h_v) + \alpha_3(l_t)$$

Model parameters are defined in Table 1. It should be noted that independent parameters in equation [4] can be rewritten as function of the annual ridership. Thus, equation [4] can be used to evaluate the annual operating costs of RFBS as function of annual ridership. An example is provided in section 4.

3.3.2 COTS

COTS is a reasonable option for proving DRT services in low demand areas. A single taxi can serve multiple passengers depending on their departure times, and trip origins and destinations. The use of an efficient trip planning and routing algorithm is essential for improving the performance of COTS.

Based on the guidelines provided in taxi bylaws, the annual operating cost model for COTS could be formulated as in equation [5], which includes a base fare, time and distance related costs. In equation [5], for each trip (r), i and j represent the stop ID corresponding to the trip origin and destination, respectively. Model parameters are defined in Table 1.

[5] $$C_R = \sum_{r=1}^{R} \left[\beta_0 + \beta_1 \left(\frac{TC_r - \gamma_1}{\delta_1}\right) + \beta_2 \left(\frac{L_r - \gamma_2}{\delta_2}\right)\right]$$

3.3.3 IHPS

Paratransit service in the Canadian municipalities is intended for providing transportation to the people who are not able to use FRBS. It is a scheduled, ride shared, and door-to-door service. IHPS is operated by the City and its available paratransit fleets to deliver a scheduled, ride shared service as per customers' requests. The only difference is that IHPS transports clients from defined origins to defined destinations (similar to fixed bus route stops) instead of door-to-door service. To develop a cost model for IHPS, the unit costs of operation, such as the cost per vehicle service hour, and the cost per vehicle traveled distance are required. However, such detailed information may not be often available. Alternatively, equation [6] is proposed to estimate IHPS operating costs which is only based on the vehicle service hour (Ts_r) and deadheading time (Td_r). Deadheading time in this case refers to the periods when there are no passengers on board for each service. Canadian public transportation agencies generally estimate the unit cost per vehicle service hour for their paratransit services as part of their financial analysis process. Model parameters in equation [6] are defined in Table 1.

[6] $C_R = \rho \times \sum_{r=1}^{R} (T_r) = \rho \times \sum_{r=1}^{R} (Ts_r + Td_r) = \rho \times \sum_{r=1}^{R} (\frac{l_r}{s_r} + Td_r)$

4 MODEL APPLICATION

Bus route 14 in Regina is used as a case study to demonstrate the application of the proposed analysis methods in this paper. Route 14 is 9.84 km long with annual ridership of 9,954 passengers and 26 stops in both directions. Considering low ridership trends, provision of DRT service is a viable option to improve the economic efficiency of route 14. Bus route 14 is located in south east of Regina, and serves a mixed land use area as it passes through commercial, institutional, open space/recreational, and residential areas. Required data for model development and calibration included hourly, weekly, monthly passenger boarding at bus stops, operating costs 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, collected in 2015 by Regina Transit Services for all bus routes in Regina.

4.1 Calibration of FRBS Operating Cost Model

To calibrate the cost model indicated in Equation [4], Regina's bus route data in 2015 were analyzed. As shown in Table 2, significant correlations were observed between, fleet size (n), vehicle service hours (h_v), and vehicle traveled distance (l_t). Thus, independent parameters were examined one-by-one for model development.

Table 2: Correlation analysis for FRBS cost model parameters

	C_R	n	h_v	l_t
C_R	1			
n	0.8502	1		
h_v	0.9997	0.8506	1	
l_t	0.9774	0.7826	0.9773	1

It was found that FRBS operating cost can be modeled with high accuracy (adjusted R^2=0.95) as function of vehicle service hours (h_v). Equation [7] shows the regression model developed for FRBS operating costs. Model parameter was found statistically significant (p=0.05).

[7] $C_R = 91.80 \times h_v$

Vehicle service hours (h_v) in equation [7] can be rewritten as the sum of total service hours during peak and off-peak hours:

[8] $h_v = v_p \times h_p + v_r \times h_r$

In equation [8], v_p represents the required fleet size during peak hours which can be estimated using equation [9]:

[9] $$v_p = \frac{L \times P_{max}}{s \times C \times LF}$$

Assuming a linear relationship between design demand (P_{max}) and average hourly passenger boarding (R_h), and considering equation [1], equation [10] can be derived:

[10] $$\gamma = \frac{P_{max}}{R_h} = \frac{P_{max} \times (h_p + h_r)}{R}$$

By solving equation [10] for design demand (P_{max}), equation [11] can be derived:

[11] $$p_{max} = \frac{\gamma \times R}{h_p + h_r}$$

Consequently, equation [12] can be derived by combining equations [9] and [11]:

[12] $$v_p = \left[\frac{L \times \gamma \times R}{s \times C \times LF \times (h_p + h_t)}\right]^+$$

Finally equation [13] is derived by combining equations [7], [8], and [12]:

[13] $$C = 91.80 \times \left(\left[\frac{L \times \gamma \times R}{s \times C \times LF \times (h_p + h_t)}\right]^+ \times h_p + v_r \times h_r \right)$$

Definitions of the parameters are provided in Table 1. It should be noted that equation [13] relates annual bus ridership to total annual operating costs. The values of other dependent parameters in equation [13] were assumed or estimated by analyzing the data provided by the City of Regina, which are shown in Table 3. Bus design demand (P_{max}) at MLS and the ratio of design demand to average hourly passenger boarding (γ) for bus route 14 was estimated based on the methodology described in section 3.2 using 2015 bus ridership data.

Table 3: The values of the parameters used in Equation [13]

Parameter	L	γ	s	C	LF	h_p	v_r	h_r
Value	9.84 km	1.219	19.68 km/hr	*67	*0.9	251 hr/yr	1	1,096.83 hr/yr

* Assumed values

4.2 Calibration of COTS Operating Cost Model

Equation [5] was used as the basis for developing an operations cost model for COTS. The second term in equation [5] represents additional charges for the time spent in congestion. Bus route 14 serves a subdivision with very low traffic volumes and uncongested roads. Thus, the second term in equation [5] was excluded. The third term in equation [5] represents the distance based taxi fare component. As shown in equation [14] the average trip distance (τ) was estimated based on the annual OD matrix and the shortest distanced between all the stops. Bus ridership data in 2015 was analyzed based on the methodology described in section 3.2 to estimate the annual OD matrix.

[14] $$\tau = \frac{PD_S}{R}$$

PD_s represents the total passenger travelled distance which is calculated by summing the product of OD flows (F_{ij}) and the shortest distances (D_{ij}) from stop i to j. k represents the total number of stops.

[15] $$PD_S = \sum_{i=1}^{k} \sum_{j=1}^{k} (F_{ij} \times D_{ij})$$

Given m as the average number of passengers on board for each taxi trip, equation [5] can be written as:

[16] $C_R \approx \frac{R}{m}[\beta_0+\beta_2\left(\frac{\tau-\gamma_2}{\delta_2}\right)]$

Estimated and assumed model parameters are shown in Table 4.

Table 4: The Values of the Parameters Used in Equation [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 km

* Assumed values

4.3 Calibration of IHPS Operating Cost Model

Similar to COTS operating cost model, τ and m were applied to simplify the original IHPS operating cost model formulated in equation [6]. Equation 17 shows the simplified IHPS operating cost model. All variables in equation [17] are defined in Table 1.

[17] $C_R \approx \rho \times \frac{R}{m} \times (\frac{\tau}{s} + f \times Td_{max})$

The values of ρ and s were set to $63.50/hr and 19.68 km/hr based on the data provided by the city of Regina. The deadheading time is defined as a percentage ($0 \leq f \leq 100$) of Td_{max} which is the average of maximum deadheading time for all trips. For each trip from stop i to j, given L_i and L_j as the distance from the dispatch center to stops i and j, and F_{ij} as the OD flow, the average maximum deadheading time Td_{max} can be estimated using equation [18]. k represents the total number of stops.

[18] $Td_{max} = \frac{\sum_{i=1}^{k}\sum_{j=1}^{k}[F_{ij} \times (L_i + L_j)]}{s \times R}$

4.4 Comparisons of FRBS, COTS, and IHPS Operating Costs as Function of Annual Ridership

Figure 6 shows variations of the operating cost models as function of annual ridership for FRBS, COTS, and IHPS services. Line 1 represents FRBS cost model (equation [13]). A single bus can serve both peak and off-peak hours on route 14 until the ridership reaches 132,573 passengers per year, at which an additional bus is required to serve peak hours. Line 2 and Line 3 are drawn based on Equation [17]. Line 2 represents the worst scenario for IHPS assuming m=2 and f=50%, which means that paratransit vehicles serve only two passenger on average per each service and the deadheading time is 50% of Td_{max}. Line 3 represents the best scenario for IHPS operation denoting that every paratransit vehicle carries 5 passengers on average while the deadheading time is 20% of Td_{max}. Equation [16] was used to produce Line 4 and Line 5 for COTS operating cost model. Line 4 represents the worst scenario for COTS operations and implies that every taxi delivers only one passenger at a time. Line 5 represents the best scenario (highest efficiency). In this scenario, each taxi is always fully loaded (m=3) between origin and destination stops. The analysis results indicate that the average number of passengers per vehicle (m) and deadheading time (for IHPS) are some of the most important parameters in determining the operating cost of DRT services. It should be noted that the best and worst scenarios are not realistic. However, they identify the feasible ranges for each DRT service cost model based on different values of m ($1 \leq m < 10$ for IHPS; $1 \leq m < 3$ for COTS). Based on Figure 6, the following results can be observed for route 14 (inequalities compare the cost performance of each service):

- COTS always performs better than IHPS considering the worst scenarios,
- IHPS always performs better than COTS considering the best scenarios,
- When $1 \leq R < 6{,}958$, COTS>IHPS>FRBS, considering the worst scenarios, and
- When $1 \leq R < 36{,}553$, COTS>IHPS>FRBS, considering the best scenarios.

Although some of this observations are obvious, the critical values of ridership for switching from one service to another can be determined based on some simple assumptions. As the annual ridership for route 14 is 9,954 a minimum required average vehicle occupancy rate can be calculated so that replacing FRBS with COTS or IHPS will result in cost savings and better economic performance. Figure 6 can be reproduced for any other bus route based on more realistic values for m and deadheading time. The results of the analysis can be used by transit planners to compare the efficiency of DRT and FRBS services in low demand areas.

5 SENSITIVITY ANALYSIS

The proposed analysis method enables evaluating the sensitivity of the operating costs due to variations in other input parameters. For example, Figure 7 shows the impact of changing the operating speed (s) of FRBS and IHPS by ±10% (indicated by 0.9s and 1.1s) on their operating costs. Change in the average operating speed affects FRBS cost model as the required fleet size will be affected. The addition of another bus is required in lower ridership if operating speed is reduced, and vice versa. On the other hand, lower operating speed will result in higher operating costs for IHPS, and vice versa. The new intersection points of operating cost models can be determined accordingly to compare the performance of each service based on the best and worst operating scenarios.

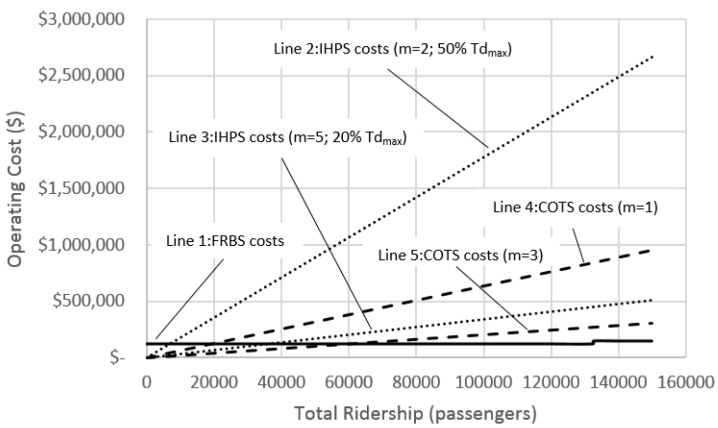

Figure 1: The relationship between operating costs and annual ridership for FRBS, COTS, and IHPS

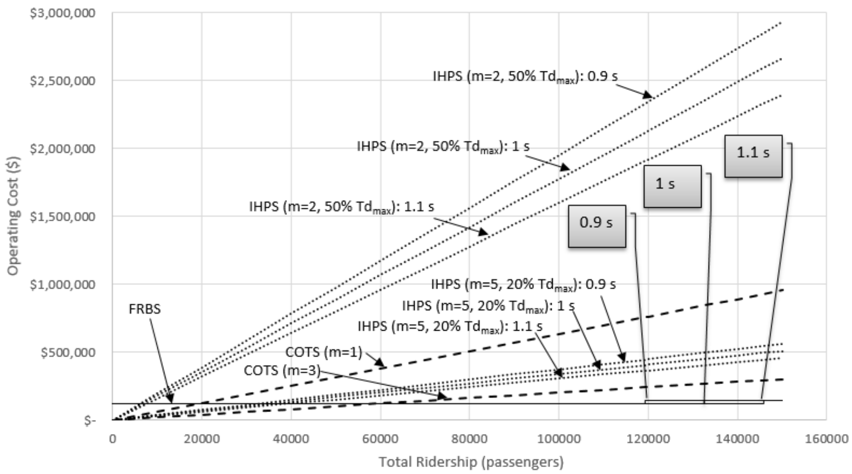

Figure 2: Sensitivity analysis for average driving speed

6 CONCLUSION

In this study feasibility of offering DRT services in low demand areas was investigated. Analytical models were proposed to evaluate and compare the operating costs of regular bus and demand responsive transit services. Two DRT services were considered i.e. COTS and IHPS. Appropriate cost models were developed for each service type to describe the operating costs as function of the annual ridership. The proposed models enable determining the critical values of annual ridership to switch from FRBS to COTS or IHPS and vice versa. Vehicle service hours was found to be the main independent parameter for modeling FRBS operating costs. The cost model for COTS included basic, time dependent, and distance based fare components. For IHPS the cost model was developed based on the unit cost for vehicle service hours. Applications of the proposed models were demonstrated using a low demand bus route in Regina. For DRT services it was shown that, operating costs are strongly related to average vehicle occupancy rate and deadheading time (for IHPS). The proposed methods in this research are based on several assumptions which should be refined and validated to generalize their application. For example, a linear relationship was assumed between the bus design demand and the average hourly ridership. This assumption should be evaluated using historical bus ridership data. In this study, passenger alighting was modeled using passenger boarding data based on the assumption of symmetry between passenger boarding and alighting ratios which should be validated using field surveys. It should be noted that the best and worst case scenarios for COTS and IHPS cost models were 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. Finally, in this study only the operating costs were considered as the main decision criteria to switch from FRBS to DRT services. However, other important criteria such as level of service and user costs including wait time and in vehicle time should be included in the analysis, which will be considered in the future extensions of this research.

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References

Abbas, K. A., and M. H. Abd-Allah. 1998. Estimation and Assessment of Cost Allocation Models for Main Transit Systems Operating in Cairo. *Transport Reviews*. 19(4): 353-375.
Cherwony, W., and S. Mundle. 1980. Transit Cost Allocation Model Development. *Journal of Transportation Engineering*. 106: 31-42.
Diana, M., L. Quadrifoglio., and C. Pronello. 2009. A Methodology for Comparing Distance Traveled by Performance-equivalent Fixed-Route and Demand Responsive Transit Services. *Transportation Planning and Technology*. 32(4): 377-399.
Edwards, D., and K. Watkins. 2013. Comparing Fixed Route and Demand-Responsive Feeder Transit System in Real-World Settings. *Transportation Research Record*. 3: 128-135. doi:10.3141/2352-15.
KFH Group. 2008. Guidebook for measuring, assessing, and improving performance of demand-response transportation. *TCRP report 124*. Washington DC: Transportation Research Board. 132.
Laws, R., M. Enoch., S. Ison., and S. Potter. 2009. Demand Responsive Transport: A review of Schemes in England and Wales. *Journal of Public Transportation*. 12(1): 19-37.
Li, X., and L. Quadrifoglio. 2010. Feeder Transit Services: Choosing Bewteen Fixed and Demand Responsive Policy. *Transportation Research Part C*. 18(5): 770-780.
Navick, D. S., and P. G. Furth. 2002. Estimating Passenger Miles, Origin-Destination Patterns, and Loads with Location-Stamped Farebox Data. *Transportation Research Record 1799*, TRB, National Research Council, Washington, D.C. 107-113.
Palmer, K., M. Dessouky., and Z. Zhou. 2008. Factors Influencing Productivity and Operating Cost of Demand Responsive Transit. *Transportation Research Part A*. 42(3): 503-523.
Rufolo, Anthony M., James G. Strathman, Eric Kuhner, and Zohngren Peng. 1995. Assessment of Demand Responsive Versus Fixed-Route Transit Service: Tri-Met Case Study. *Final Report TNW95-08.* Seattle, WA: Transportation Northwest (TransNow), University of Washington.
Scott, R.A. (2010). Demand responsive passenger transport in low-demand situations. *NZ Transport Agency research report*. 425(116).
Tsygalnitsky, S. 1977. Simplified Methods of Transportation Planning. thesis presented to Massachusetts Institute of Technology, Cambridge, Mass., in partial fulfillment of the requirements for the degree of Master of Science.