DEMAND-RESPONSIVE TRANSIT DESIGN METHODS AND APPLICATIONS FOR MINIBUS TAXI HYBRID MODELS IN SOUTH AFRICA

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ABSTRACT

Demand-responsive technology has long had theoretical potential in urban mobility (Jokinen, 2011), but the failure of microtransit companies in the US and UK should be noted as cautionary to the trial or implementation of demand-responsive services without adequate modelling. This paper attempts to produce a numerical model to the concept of "New Generation Services" outlined in the City of Cape Town MyCiti Business Plan 2018, or the "Hybrid Model" that has entered the current transport planning lexicon in South Africa since 2017. The authors aim to demonstrate a method for how detailed on-board survey data can be extrapolated and collated to prove the business case for minibus-taxi operators to shift from the current inefficient "load-and-go" operation to a more direct demand-responsive service. This paper presents a description of a methodology that is followed to capture test data, develop supply and demand models, run simulations and optimize the system to rationalize operations and business case for various operators. The numerical model is a demand and supply model, where the recommended fleet size is determined from the current passenger demand in the service network. In developing the demand and supply model, the data is obtained from onboard vehicle survey data. The model calculates total operating cost, revenue and carbon footprint of the current operations to the optimized and rationalized operations recommended in the model.

1. INTRODUCTION

This paper demonstrates a method that can utilize onboard survey data collected on bus systems to build demand and supply models for demand responsive transit (DRT) systems that are optimized to bring supply (fleet size) and demand to an equilibrium without fixed routes or fixed stops. As defined by Jokinen et al (2011), "DRT provides a shared transport service, which adapts dynamically to demand by routing a fleet of vehicles operating without any fixed routes or timetables." The MyCiti Business Plan 2018 (City of Cape Town, 2018) define demand-responsive technology and methodologies as those that "enable the emergence of new types of services, especially those using smaller vehicles as they are able to respond to the much more flexible matching of supply and demand that the new technological capabilities permit, especially in a collectivised manner, thus reducing cost." These two definitions both refer to an operating approach, and a way to use demand intelligence and technology to co-ordinate and operate vehicles in response to the demand as it manifests. The concept of operations for this paper makes use of minibus taxi vehicles (13-seaters) that undertake trips from door-to-door with pick-up and drop-off as close to the original destination and final destination of the user trip, without any transfers within a certain feeder zone. This operation achieves the "operational complementarity" posited by Jennings and Behrens (2017). A typical scenario for application of this method would be a demand responsive transit network in an area serving approximately 50,000 inhabitants, with a demand responsive supply of approximately 3 operators each with 35 vehicles with a seated capacity of 16 riders – and with a catchment area of 100 square kilometers (10km x 10km) – which corresponds with the parameters set out by Jokinen et al (2011).

The term “demand-responsiveness” has been mistakenly attributed as the cause of a number of negative externalities by Jennings and Behrens (2017) for informal transport operators running unsafe operations or disregarding traffic laws and other regulations. Demand-responsiveness is merely an approach to operations using demand intelligence and routing algorithms. As an operating method, it should not be associated with the poor operational management or negative externalities that manifest in the informal transport sector. The authors of this paper have the view that “the current model whereby large numbers of small-scale operators compete under the very loose control of taxi associations is regarded as one of the underlying causes of the worst features of the industry, such as speeding, poor driver behaviour and safety concerns.” (City of Cape Town, 2018).

2. DETERMINATION OF DEMAND

The model discussed in this paper was developed to determine how a population can be serviced by a rationalized demand responsive transit fleet to undertake trip-taking from residential areas to a small-town main street CBD and a regional rail station for connections for onward journeys. The service is designed to closely match the services to demand where the supply is dynamic in the response to demand. In developing the model for each simulation, the following steps in Figure 1 were followed:

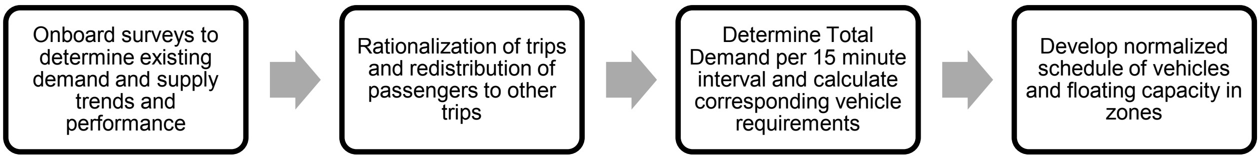

Figure 1: Steps followed in developing the DRT simulation

2.1 Data preparation - defining a trip for analysis

This paper utilizes data collected from onboard vehicle surveys and serves as the database for the development of this model on the basis of current demand and its response to the current supply. Onboard vehicle surveys that provide detailed passenger, trip and vehicle data is key for the development of the model simulation presented in this paper. The methodology adopted for this paper for onboard vehicle surveys for informal and formal public transport (paratransit, conventional bus or bus rapid transit) is discussed in a paper written by Coetzee, Krogscheepers and Spotten (SATC, 2018).

2.2 Rationalization of unproductive trips

The major focus of this paper is to demonstrate the opportunities that exist in a transport network to reduce inefficiencies in the system and optimize operations in trip-taking and fleet deployment of a shared mobility fleet. A key factor to this is by reducing the number of unproductive trips that are currently in the operations plan and practice. This reduction then increases efficiency by reducing the number of vehicles required and the distance vehicles travel daily. An unproductive trip, with regards to this analysis, is defined by a trip that has a value of 5 passengers or less per trip. This can be explained by calculating the break-even point (BEP) in measuring the number of passengers required to cover the variable cost per trip. The variable costs are a function of the distance travelled by the vehicle or veh-km (Coetzee, *et al.,* 2018).

Table 1: Break-even cost per km and minimum passenger numbers

	4 Passengers	5 Passengers	6 Passengers
Maximum Trip Distance	9.5 km (5.9 mi)	9.5 km (5.9 mi)	9.5 km (5.9 mi)
Fare per Passenger per Trip	$ 0.60	$ 0.60	$ 0.60
Variable Cost per km	$ 0.14 / mile	$ 0.21 / mile	$ 0.25 / mile
Variable Cost per Trip	$ 0.80	$ 1.20	$ 1.40

Internationally, the literature shows that DRT pilots are failing as a result of not being realistically costed, nor designed with a full understanding of the market they are meant to serve, with an average ridership of less than 3 passengers per trip (Enoch, *et al*. 2006). There have been high-profile and well-funded DRT pilots and companies that have had significant political support, generated considerable market awareness and attractive fares, but have shut down after the pilot was completed or have run out of funding before the pilot could be completed. Jokinen (2011) makes the point that critical mass is require for a fully-functioning mass DRT system to become economically viable. The authors have not found an example of a DRT system in the world that has been able to launch and run at a profit in a free market, but subsidies, promotion, protection and restrictions have always applied to DRT operations.

2.3 Redistribution of passengers from unproductive trips

Once the unproductive trips are removed, the total number of passengers from the unproductive trips remain. The passengers from the unproductive need to be redistributed as the model assumes that demand remains static. The unproductive trip passengers are redistributed to the remaining productive trips in a simple spread per hour interval. This process is repeated until the unproductive passengers are redistributed. These hourly optimized passenger totals represent the total hourly demand for an initial estimate of impact. This can be done for 5-minute, 10-minute, 15-minute or 20-minute increments as well for greater accuracy or more detailed planning. From this the peak period totals can be extracted for further analysis.

3. DETERMINATION OF CURRENT SUPPLY PERFORMANCE

3.1 Calculate seat turnover and total available seats

From the optimized data, the next step is to calculate the seat turnover and the total available seats, which represent the base- and dynamic supply. Seat turnover is defined by calculating the number of times a single seat in the vehicle is used by different individuals (“turnover”) during a single trip. The total available seats represent the supply in the system and can be expressed as base supply and dynamic supply. Transit systems with a high seat turnover ratio have a higher potential for optimization as the number of vehicles required can be reduced. A transit system that has a low seat turnover ratio has less potential to be optimized as the occupants remain seated for the full trip. In Table 2 below an example of the extrapolated demand is illustrated with the outputs of the steps above. The adjusted passengers are the redistributed passengers from the unproductive trips.

Table 2: Example of the extrapolated demand of productive trips

EXTRAPOLATED DEMAND (Less Trips)	5 AM	6 AM	7 AM	8 AM	9 AM	10 AM	11 AM	12 PM	1 PM	2 PM	3 PM	4 PM	5 PM	6 PM	Grand Total
Adjusted Pax after removal of unproductive trips	300	779	1860	1800	1300	1200	2000	1700	1300	1400	1300	1500	1600	800	18839
Trips (new value after removal of unproductive trips).	19	80	167	148	117	86	136	111	93	93	105	99	117	49	1419
Passengers per trip	16	10	11	12	11	14	15	15	14	15	12	15	14	16	
Seat Turnover Ratio	1,2	0,7	0,8	0,9	0,8	1,0	1,1	1,1	1,0	1,1	0,9	1,1	1,0	1,2	1,0
New Base Supply	259	1123	2332	2073	1641	1209	1900	1555	1296	1296	1468	1382	1641	691	19864
New Dynamic Supply	300	1123	2332	2073	1641	1209	2000	1700	1300	1400	1468	1500	1641	800	20487

The average seat turnover in this example is 1 due to the low seat turnover in the morning peak period. To calculate the dynamic supply indicated in red text in Table 2, if the seat turnover is below 1, which in this example there are a few, the base supply total is applied if the seat turnover is 1 and above the actual seat turnover value of that hour interval is applied. This can be seen when observing the 5AM and 6AM hour intervals in Table 2, where the dynamic supply of the 5AM interval has an increase in 41 seats due to the seat turnover ratio of 1.2, whereas the dynamic supply of the 6AM interval has the same value as the base supply because the seat turnover is 0.7 which is below the set ratio of 1. In calculating the dynamic supply, the oversupply can be determined. This is discussed in the following section.

3.2 Calculate total oversupply

The next step is to determine the total oversupply by calculating the difference between the total of the dynamic supply and the total passenger demand. The oversupply is calculated in each table in the model to determine the total oversupply during each phase of the analysis to illustrate the total oversupply of the current operations and the possible oversupply for the three different scenarios.

3.3 Determine fleet size per hour interval

The fleet size for the *mathematical minimum* illustrated in Table 3 is a calculation of the absolute minimum number of vehicles required per hour to serve the demand. This output is volatile as the demand fluctuates every hour; therefore the *practical operations* section Table 4 illustrates a normalized output of fleet size requirements to service the demand.

Table 3: Example of the mathematical minimum output

Mathematical Minimum	5 AM	6 AM	7 AM	8 AM	9 AM	10 AM	11 AM	12 PM	1 PM	2 PM	3 PM	4 PM	5 PM	6 PM	Grand Total
Min veh required -Mathematical	6	15	37	36	26	24	45	37	31	31	26	33	32	16	
Min Veh Mathematical Trips	19	46	111	107	77	71	136	111	93	93	77	99	95	49	1184
Min Veh Mathematical - Base Supply of Seats	259	649	1550	1500	1083	1000	1900	1555	1296	1296	1083	1382	1333	691	16577

4. DEMAND-RESPONSIVE OPERATIONAL PLAN

The *practical operations* fleet size is manually assigned based on the results to generate a normalized output of fleet size requirements to serve the demand. Instead of having a fluctuating fleet size, which would prove challenging in practical operations terms, a normalized fleet size is spread over the entire day by bringing supply close to the demand. The seat turnover value can be manually edited in the model. In the first iteration of the demand and supply model a seat turnover ratio of 1.2 is used as it is the constant average seat turnover value throughout all days surveyed and provides a normalized supply throughout the operational day. This can be seen in Table 4 where the seat turnover is manually applied. The value can also be adjusted once the second hypothesis is complete and more data is available to better understand current operations.

Table 4: Example of the practical operations output

Practical Operations	**5 AM**	**6 AM**	**7 AM**	**8 AM**	**9 AM**	**10 AM**	**11 AM**	**12 PM**	**1 PM**	**2 PM**	**3 PM**	**4 PM**	**5 PM**	**6 PM**	**Grand Total**
Practical Operations Vehicles	6	16	32	32	32	32	32	32	32	32	32	32	32	16	
Practical Operations Trips	18	48	96	96	96	96	96	96	96	96	96	96	96	48	1170
Base Supply of Seats of Core Operations	252	672	1344	1344	1344	1344	1344	1344	1344	1344	1344	1344	1344	672	16380
Dynamic Supply of Seats of Core Operations (Seat turnover ratio of 1,2)	302	806	1613	1613	1613	1613	1613	1613	1613	1613	1613	1613	1613	806	19656
Passenger Demand	300	779	1860	1800	1300	1200	2000	1700	1300	1400	1300	1500	1600	800	18839

The vehicle fleet size in this step is not calculated automatically, rather by manual input to smooth out the supply of vehicles throughout the day. In Table 4, the supply of seats only just meets the passenger demand and could have negative implications on the network with regards to passenger waiting times and overloading the vehicles. This leads to the final *practical operations plus reserve* section where a reserve fleet of 6 vehicles per fleet is operational to absorb the spikes in demand, and create spare seat capacity, to ensure that passengers do not experience long waiting times, as well as provide an opportunity for a service to meet door-to-door demand when required. The total fleet size is thus calculated by adding 6 vehicles to the *practical operations* as the reserve fleet and will only be deployed when the demand increases rapidly in the mornings and will stop operating when the demand decreases in the afternoon.

In understanding the current fleet operations, the reserve fleet size of 6 was identified from the analyzing the passenger demand. The reserve fleet size of 6 is derived from the optimized fleet size in the final output of the model and varies between 10-15% of the operation fleet size. After incorporating the 6 reserve vehicles into the model in the *practical operations plus reserve* step, the supply of the extra floating seats absorbed the abnormal spikes in demand sufficiently and therefore reduces the operational fleet size needed to serve the demand throughout the day.

Table 5: Example of the practical operations plus reserve fleet output

Practical Operations + Reserve 6	5 AM	6 AM	7 AM	8 AM	9 AM	10 AM	11 AM	12 PM	1 PM	2 PM	3 PM	4 PM	5 PM	6 PM	Grand Total
Practical Fleet + Reserve 6	6	22	38	38	38	38	38	38	38	38	38	38	38	22	
Practical Fleet + Reserve 6 Trips	18	66	114	114	114	114	114	114	114	114	114	114	114	66	1404
Base Supply of Seats	252	924	1596	1596	1596	1596	1596	1596	1596	1596	1596	1596	1596	924	19656
Dynamic Supply of Seats	302	1109	1915	1915	1915	1915	1915	1915	1915	1915	1915	1915	1915	1109	23587
Passenger Demand	300	779	1860	1800	1300	1200	2000	1700	1300	1400	1300	1500	1600	800	18839

Table 5 above allows for the manual inputs of a reserve fleet of 6 reserve vehicles for each hour interval when the passenger demand increases from 6AM. The 6 reserve fleet creates additional supply of seats in the network and increases the fleet capacity to serve passenger demand. The three examples illustrated in the tables above are from the learning dataset for a one full day of operations. From the results in these tables the total fleet sizes and dynamic supply can be illustrated and compared to the passenger demand to analyze whether the supply of seats is adequate to serve the demand and accommodate spikes in the passenger demand during the entire operating day.

Table 6: Example of the complete results of the demand vs dynamic supply

Demand/Supply (Dynamic Seats)	5 AM	6 AM	7 AM	8 AM	9 AM	10 AM	11 AM	12 PM	1 PM	2 PM	3 PM	4 PM	5 PM	6 PM	Daily	Ratio
Passenger Demand	300	779	1860	1800	1300	1200	2000	1700	1300	1400	1300	1500	1600	800	18839	
Practical Operations	302	806	1613	1613	1613	1613	1613	1613	1613	1613	1613	1613	1613	806	19656	1,043
Practical Operations and Reserve 6	302	1109	1915	1915	1915	1915	1915	1915	1915	1915	1915	1915	1915	1109	23587	1,252

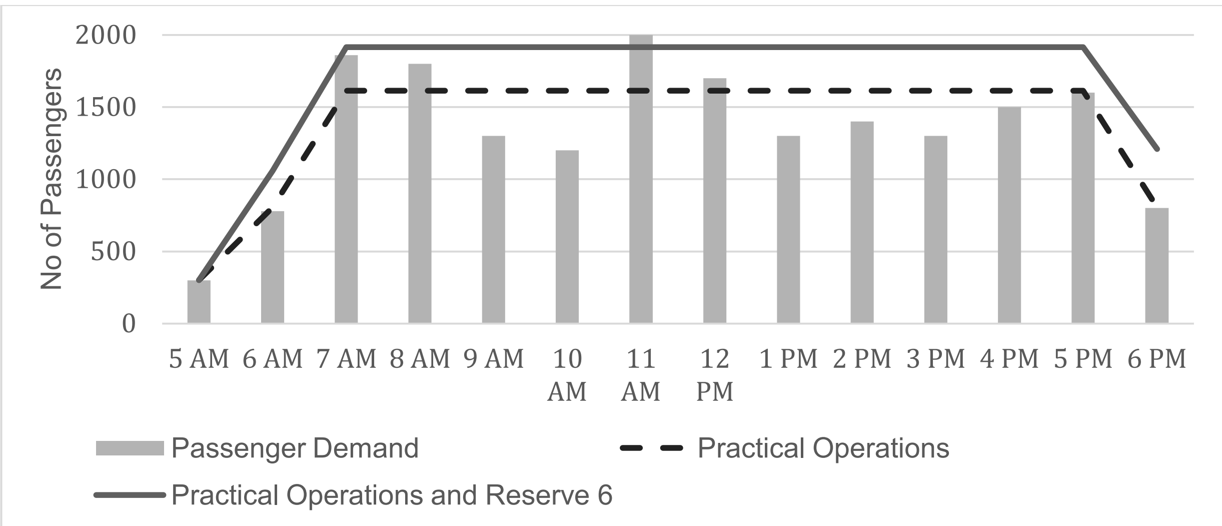

Figure 2: Passenger demand (bar) versus Practical Operations (off-peak) plus Reserve 6 (peak)

In Figure 4 the outputs of the model is illustrated to see the fleet size operations per hour and the supply and demand per hour interval. Here one can see how the reserve fleet absorbs the abnormal/additional spikes in demand at any given hour of the day. As seen in the right-hand figure above, the *mathematical minimum* supply of seats follows the demand fluctuations and suggests a fluctuating fleet size per hour interval. This will prove challenging from a practical operations perspective, however the normalized fleet size with the reserve fleet serves as an indicator for an applicable operations plan. The operating fleet size recommendation varies per day surveyed as the data returns a different passenger demand pattern each day of operations. To determine the exact recommended fleet size for the entire network, the total fleet sizes recommended in the model for each day's data is plotted in figure 5 below. The bar graphs illustrate the *practical operations* and *practical operations plus reserve* fleet sizes which fluctuate according to the data collected for each day mapped.

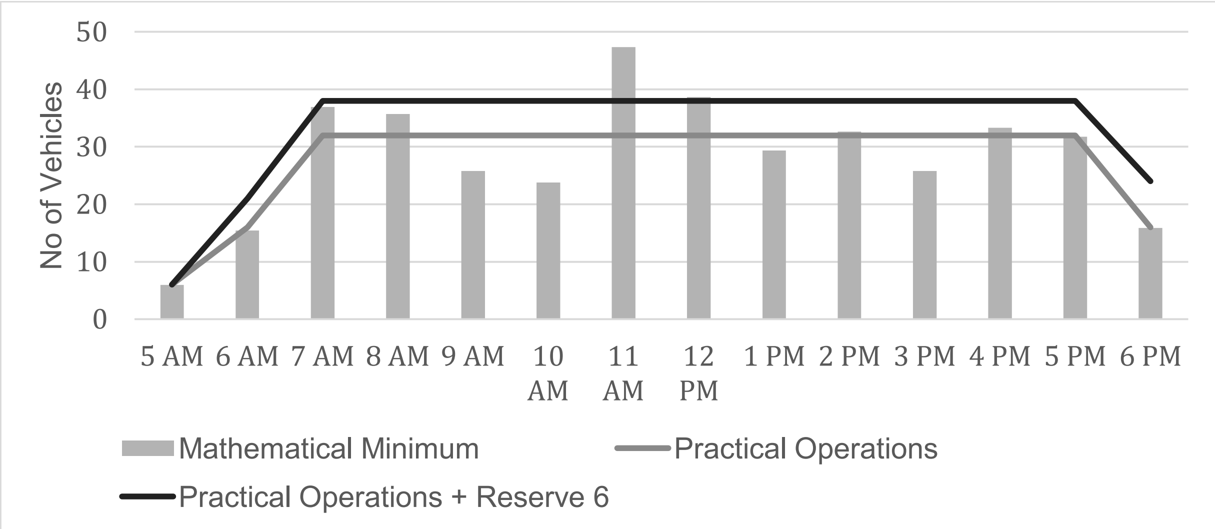

Figure 3: Fleet size (reduced from original 78) to practical operations plus Reserve 6

5. FINANCIAL IMPLICATIONS (SAVINGS) DUE TO DEMAND-RESPONSIVE OPERATIONAL PLAN

The decrease from the current operational fleet size of 78 vehicles to the recommended 38 vehicles is a reduction of 40 vehicles. This has major implications for all manner of operational costs – asset recapitalization, the number of required drivers, depot and sleeping ground facilities and most dramatically, fuel. These are material savings due to the reduction in fleet and in operating kilometers – and illustrate the potential of demand-responsive practices in the delivery of public transport feeder and distribution services complementary to mass-transit high-volume corridor development, which is where South Africa finds its public transport development.

Table 7: Systems profitability and reduction in emissions

Fleet A	Current Operations	Recommended Operations	Change (#)	Change (%)
Number of vehicles	78	38	40	-50%
Number of Seats per day	29 624	23 587	6 037	-20%
Number of Riders per day	18 840	18 840	0	0%
Number of Trips per day	2 116	1 404	712	-34%
Average Trip Length (km)	8	8	0	0%
km driven per day	16 928	11 232	5 696	-34%
km driven per year	5 078 400	3 369 600	1 708 800	-34%

In Table 7 above, the impact of the decrease in operational fleet size is illustrated and quantified for a typical weekday which is then annualized for an entire year of weekday operations. The reduction in operational fleet size reduces the annual costs by decreasing the total trips and kilometres travelled to serve the passenger demand of the system.

The annual revenue remains constant as the simulation assumes demand remains static, thus the systems profitability shifts from a loss of R6.78 million to a profit of R9 million due to the distance travelled per day being reduced, a 30% savings but a radical improvement by optimizing the rationalized fleet and the associated costs. The negative profit figure is an accounting for management cost inputs (which are not accounted for in a lot of informally-run operations), safety and quality measures which are not adhered to as well as an allowance for recapitalization and maintenance (which is also not directly managed in the current operations). The same costs have been left out of the recommended operations business plan to allow for parity. However, it is worth noting that there is potential fund of R9 million per year to allow for recapitalization, maintenance and management fees due to a change in operating rules and design. This is an indicative value on benchmark costing and a number of operational assumptions, and further work is required to develop a detailed costing model to establish an accurate operational dividend due to DRT.

Table 8: Systems profitability and per vehicle profitability

Fleet A	Current Operations	Recommended Operations
Annual Systems Profitability	- R6 782 040,00	R9 042 720,00
Daily Revenue per vehicle	R1 932,21	R1 932,21
Daily Cost per vehicle	R2 222,04	R1 545,76
Nett Daily Revenue per vehicle	-R289,83	R386,44

Not only does this reduction in vehicle fleet size have a significant impact on the annual revenue and costs of an operation, but there is a major impact on CO2 emissions due to the reduction of unproductive trips in the demand-responsive scheme. As seen in table 7, the savings in CO2 emissions results in a saving of 1 170 tons of CO2 emissions per annum for a 10kmx10km area of Cape Town.

Table 9: Reduction in emissions projected by DRT operational plan

Fleet A	Current Operations	Recommended Operations	Change per day	Change (%)
CO2 kg/km	0,45	0,33	0,12	-27%
Emissions (t)	7,6	3,7	3,9	-51%

Although the reduction in vehicle fleet sizes are environmentally beneficial and reduce the costs of operations for the transit industry, as discussed in the paper presented by Saddier & Johnson (SATC, 2018) the reduction in vehicles may lead to a number of job losses in the driver sector. However, it is the authors' assertion that this presents an opportunity to normalize labour practices in the informal transport sector to be in line with SARPBAC requirements and thus can deliver another positive result if adopted at scale.

6. CONCLUSION

Demand-responsive transit (DRT) has a lot of potential in South African cities to be the mechanism that integrates the formal and informal transport systems. Feeder and distributor services that are truly complementary to quality bus, commuter rail or BRT can be designed and deployed at a significantly lower rate to conventional bus feeder services using a high-quality and rationalized minibus-taxi fleet in each feeder area.

From the simulation discussed in this paper it is evident that optimizing and rationalizing operations of a demand responsive transit service reduces operational costs, increases systems profitability and reduces the carbon footprint of the service to run more sustainably than any current alternative. By providing a scheduled fixed route service that serves the passenger needs to a certain extent, the demand responsive service is able to deviate from the fixed route increasing the patronage and flexibility of the transit network. The work following this paper would investigate the impact on the numerical model by measuring the design and operations of a combined scheduled fixed route services and demand responsive transit service is provided in a similar study area.

The method in this paper outlines a practical and attainable concept of operations that aligns with the “New Generation Services” or “Hybrid Model” that has been well-argued and established as a rational design approach for the development of Integrated Public Transport Networks (Jennings and Behrens, 2017). We recommend more research is done in the components of the concept and service design, as well as developing benchmarks and Levels of Service so that the service designs that are developed in the next few years in South African cities can be technically evaluated and assessed for applicability to the IPTN scheme it is meant to compliment. Jokinen (2011) focused on the service promise concept (which this paper does not explore), and would be the rules and logic in a DRT system development.

For policy-makers and officials investigating informal public transport reform, bus contract reform or complementary feeder services for mass public transport – technology-driven demand-responsive transit (DRT) may produce an economic model that is attractive to the minibus-taxi sector to engage in the change needed to reorganize public transport in South African cities. This paper has advanced the numerical experiments first posited by Jokinen (2011) by creating a practical operational plan based on existing onboard survey data of a large area in a South African city and developing a vehicle fleet size to respond to a developed demand graph. The next step in this process would be to run this system in a trial in the field to establish the enablers and barriers to a successful DRT operation including institutional, regulatory, operational, capacity and other challenges to a DRT system – as well as understanding the various ways that DRT could be implemented.

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