ARTICULATED DENSITY: A STUDY OF ITS POTENTIAL EFFECTS ON THE FINANCIAL SUSTAINABILITY OF SOUTH AFRICAN BRT CORRIDORS

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ABSTRACT

The financial sustainability and continued roll-out of South African Bus Rapid Transit (BRT) networks has been questioned. The unique spatial structure of South African cities, in which the majority of residents live toward the urban periphery, has created an unsupportive land use environment and large catchment areas for the BRT trunk service routes. This paper investigates the potential for 'articulated density' to overcome this barrier to financial sustainability. This relatively new land use indicator refers to how strategically population density is distributed over a city, in relation to trunk service proximity. The paper utilises a simplified public transport corridor operating cost model to test the effects of varying degrees of population density and articulated density on the financial sustainability of a hypothetical BRT service. When tested in typical South African conditions, population density is found to have a weak relationship with the viability of the BRT service, due to the heavy reliance on low-efficiency feeder services. Furthermore, the large catchment area of the trunk route results in the BRT's operational limit for passenger volume being encountered at gross population densities as low as 50 persons/ha. Density articulation is found to have a much stronger influence, as it diminishes the reliance on the feeder routes. However, if the catchment area of the BRT trunk corridor is reduced, the proportion that does not require feeder services increases along with the influence of population density. It is argued, therefore, that South African city authorities need to either prioritise density articulation in current BRT corridors or reduce their length and catchment area in order to attain more sustainable services.

1   INTRODUCTION

Many cities in the 'global south' face mounting pressures from rapid urbanization, population growth and rising income inequality. The successful integration of public transport and land development planning is likely to be central in determining how effectively these cities manage these pressures. Some research – associated with the advent of bus rapid transit (BRT) systems – into how best to integrate public transport and land development planning has been undertaken in Latin America and Asia, (Cervero & Dai, 2014; Kash & Hidalgo, 2014; Lindau, Hidalgo & de Almeida Lobo, 2014; Cervero, 2013; Suzuki, Cervero & Iuchi, 2013). While a number of Sub-Saharan African cities, particularly in South Africa, have commenced large scale

public transport reform, little research has been undertaken to date on appropriate public transport-land use integration in these contexts.

The initial phases of BRT corridor implementation in South African cities have highlighted the importance of supportive urban forms in facilitating public transport services that are not dependent upon unsustainable operating subsidies. The City of Cape Town's latest review of its Comprehensive Integrated Transport Plan (CITP), for instance, states that "*[t]he operational requirements to run road-based public transport at the levels of service required by the CITP 2013-2018, in the current urban form of Cape Town, are proving to be financially unsustainable and could lead to significant long-term implications for the future roll-out of road-based public transport…Dispersed urban form leads to passenger numbers being low along many routes resulting in demand best met by small vehicle sizes and longer headways*" (CCT, 2014). The City of Johannesburg has come to similar conclusions in its Rea Vaya Phase 1C Sustainability Study (CoJ, 2013). Clearly a better understanding of the prerequisite land use conditions for high quality BRT systems is required, and technology choices should be made with due regard to the prevailing urban form (Del Mistro & Bruun, 2012).

Density has been widely accepted by South African city planning authorities as an important land use prerequisite, resulting in the formulation of density targets and densification policies (Jones, 2014). On its own urban gross population density is, however, a fairly weak predictor of viable public transport. Cooke & Behrens (2014) demonstrate that the concept of articulated density offers a better indicator of supportive urban form. This paper reports some of the findings of a study undertaken to understand the interrelationship between gross population density, density articulation and viable road-based public transport services at a corridor scale, focussing specifically on BRT corridor services in the South African context. The paper is divided into five sections. The following section summarises the available literature on the density-public transport relationship. Section 3 explains the study method, in the form of simulated public transport system configuration-urban form relationships using a corridor operating cost model. Section 4 presents the study findings, and section 5 concludes with a discussion on their implications for policy and further research needs.

2 LITERATURE REVIEW

2.1 Population density

Population density is defined in this paper as the number of people residing within a specified gross area, per unit area. Population density affects the volume of passengers that utilise a public transport service (Newman, 1989). Championed by (Newman & Kenworthy, 1989) in the 1980s, density has garnered much of the attention in the land use-transport interaction research. Their research spawned a host of investigations which has yielded a broad literary base for this relationship. From the studies done, the majority are in agreement with their conclusion that population density is the most significant spatial factor in determining the way people travel. Jones (2014:26) summarises the density thresholds required for viable public transport services offered by various authors. International empirical evidence suggests that urban gross population densities in the range of 140-190 persons per

hectare (p/ha) are required to attain viable and successful public transport (Cooke & Behrens, 2014).

Various South African cities have developed densification policies that set density targets in relation to both the entire city area and public transport corridors (see Table 1).

Table 1: *Densification targets in selected South African cities (after Jones, 2014)*

|	MUNICIPALITY				
	Cape Town (CoCT, 2012)	**Tshwane** (CoT, 2012)	**Johannesburg** (CoJ, 2010)	**Nelson Mandela Bay** (NMBM, 2007)	**eThekwini** (eThekwini Municipality, 2013)
EXISTING GROSS POPULATION DENSITY FOR THE URBANISED CITY AREA (persons/ha)	47	35	43	23	39
TARGET GROSS POPULATION DENSITY FOR THE URBANISED CITY AREA (persons/ha)	83	-	-	78	79
TARGET GROSS POPULATION DENSITY FOR PUBLIC TRANSPORT TRUNK CORRIDORS (persons/ha)	208	150	232	238	209

2.2 Density articulation

The distribution of density across space is a recent addition to the group of urban form indicators. Strategically distributed density is referred to as 'articulated density' (Suzuki, Cervero & Iuchi, 2013) or 'differentiated density' in the Chinese literature (Zhang, 2007). 'Density articulation' is proposed in this paper as a measure for how strategically the population density is distributed over the city area with regard to public transport trunk service proximity. The distribution of density affects trip lengths by placing the majority of public transport users within walking distance of the trunk route, negating the need to take a feeder service (Suzuki, Cervero & Iuchi, 2013). At the time of writing, only one study could be found that explores the effect of density distribution on public transport viability (Sivakumaran et al. 2014).

3 STUDY METHOD

Due to scarce empirical data on South African land use characteristics and public transport operating costs, simulation research is necessary to study public transport-urban form relationships. A public transport corridor operating cost model was therefore developed to simulate the effects of varying land use environments on public transport systems. The model expands an earlier version developed by Del Mistro & Bruun (2012). This paper focuses on just the simulation scenarios involving population density, density articulation and mode technology related to a BRT service.

3.1 Network development

Given the radial nature of many South African public transport networks, the model represents a triangular transport corridor terminating at a Central Business District (CBD) (see Figure 2). The catchment area of the corridor is divided into 42 Traffic Analysis Zones (TAZs), each with specific land use types and characteristics. In Figure 2 the green TAZs represent areas that are within walking proximity of the trunk service (i.e. less than 2 km away) to negate the need for an additional feeder service. Outside of these TAZs, the maximum allowable walking distance to feeder services is 1 km. These distances conform to the guidelines of the South African *Public Transport Strategy* (DoT, 2007) and the *White Paper on National Transport Policy* (DoT, 1996). The blue TAZs are serviced by feeder routes and the beige TAZs represent the parts of the corridor catchment that are not serviced by feeder routes. The latter zones improve the realism of the model as the coverage of a public transport system is often less than 100%. The *Public Transport Strategy* aims to achieve 85% coverage of a metropolitan city area: in accordance, this model achieves 84% coverage (DoT, 2007).
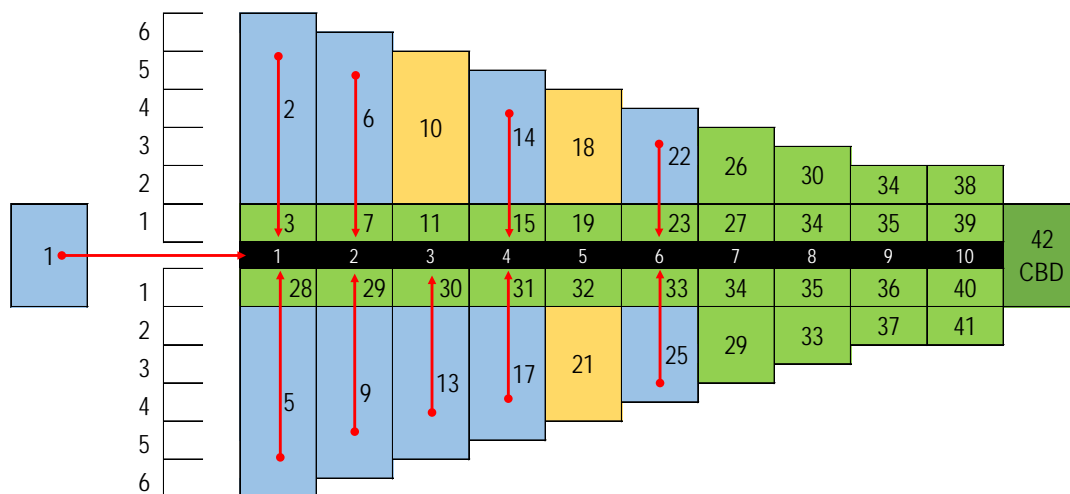
Figure 1: *TAZ layout of the simulated transport corridor*

The model is comprised of one trunk service route (thick black line) and ten feeder service routes (thin red lines). The trunk route consists of 10 links, and the link with the highest passenger volume dictates its capacity. On feeder routes, all trips are assumed to start or finish at one of the two terminal points of the red lines. Capacity for the feeder route is determined by the theoretical peak volume. The length of the trunk route is 20 km, which is comparable to the 15 km of Cape Town's Phase 1A and 25.5 km of Johannesburg's Phase 1A (www.brtdata.org, 2014).

3.2 Land use input

Land use data is added to each TAZ individually. The distribution of passengers is manipulated by altering the population density of residential land uses. Across the public transport corridor, the total area of non-residential land uses is set to maintain an approximate balance between trip productions and attractions. The four land use categories include: residential; business; industrial; and retail. The South African Trip Generation Rates were utilized to calculate the trip productions and attractions for each TAZ, based on the areas of the land use types and their respective population and employment densities (DoT, 1995). The population density also determines the

expected public transport modal split based on an analysis of the empirical data from the Millennium Cities Database (Kenworthy & Laube, 2001). Within each scenario, the distribution and magnitude of the land use variables that are not being tested are given set values that represent the average South African transport corridor as closely as possible. The intensity of the land uses, and therefore the costs associated with the system, are ramped up and averaged over a period of 20 years in order to include the repayment costs of the capital investments.

3.3   Trip distribution

A gravity model was chosen to distribute the trips throughout the network, using a conventional distance decay friction factor and a beta value of 0.25 (see Masucci et al. (2013) for a description of the model's algorithm). The distances between the TAZs are calculated as route length rather than direct distance and the TAZs within close proximity to the trunk service are assumed to have no feeder distance penalty. The model undergoes nine iterations of the Furness method and cumulates the origin-destination pairs onto the nearest routes. The gravity model is run for the morning peak hour and the total number of passenger trips is then extrapolated for the entire day, for input into the costing model.

3.4   Operating costs

Operational performance and costing data for the small low-floor, bigger high-floor and articulated buses used by Del Mistro & Bruun's (2012) were updated and supplemented with new data sourced from government and parastatal agency publications. An array of costs was generated for each mode per route. Additionally, the costs for travel to and from the unserviced TAZs were added to the total, assuming that all potential public transport trips to the trunk route would have to be completed by private vehicle park-and-ride.

3.5   Output analysis

From the output of the model, four indicators were chosen for analysis: authority cost; operator cost; average trip length; and peak passenger volume.

The authority cost represents the total cost of the system to the transport authority and includes operating subsidies as well as loan repayments on capital investments. The authority cost is also an indicator of the overall viability of the system under different conditions. The model uses the gross cost contracting arrangement, whereby the operator is guaranteed a certain amount of profit over and above their expenses, and the financial risk of the system rests with the authority. The shortfall between the operator's costs, including predetermined profit, and the fare revenue is then met by the authority through a subsidy. Therefore, in this model a financially viable public transport service is one with a low cost to the authority, irrespective of the operating cost.

The cost to the operator is, nevertheless, still important. If the cost of being a public transport operator is too high, market entry and contestability would be detrimentally affected. A majority of South African public transport trips are currently being serviced by small-scale operators who would find difficulty in competing in a high cost environment (Schalekamp & Behrens, 2010).

Average passenger trip length can contribute to the viability of a public transport service. The common fare collection systems, including the distance-based system used by the model, penalize shorter trips through a base fare. The effect of the land use characteristics on average trip length, and its correlation to authority cost, can then be analysed.

The trunk route's peak passenger volume determines the capacity that needs to be supplied, and is often the determinant for the choice of mode technology. The amount of capacity that is required has significant effects on the capital and operating costs of the service.

4   RESULTS

4.1   Population density
The population density scenario simulations explore the effect of gross corridor population density on public transport system viability. The test range was between two and 400 p/ha spread evenly across the catchment area. The land use distribution approximated a generic South African city with a strong CBD, allocating 50% of the trip destinations to the CBD and the rest along the trunk route. The land use activity increased with population density to balance the trip origins and destinations. The allocated land use areas remained constant, resulting in the total population of the corridor increasing linearly with increasing density. As the costs of the system naturally increase with the number of users, the total cost to the authority or operator is difficult to compare for different values of population density. Hence, the authority and operator costs are represented as a monetary value per passenger served.

Figure 3 illustrates the four output analysis indicators for the simulated transport system at each value of population density. The upper limit of the displayed density values is 100 p/ha, as the peak passenger volume at 100 p/ha is 82 892 persons per hour per direction (p/h/d), which is beyond even the capacity of many subway systems. This high passenger volume at a moderate population density highlights the inefficient structure of the South African BRT corridor being represented. The authority cost, operator cost and average trip length are observed to remain relatively unchanged for high density values.
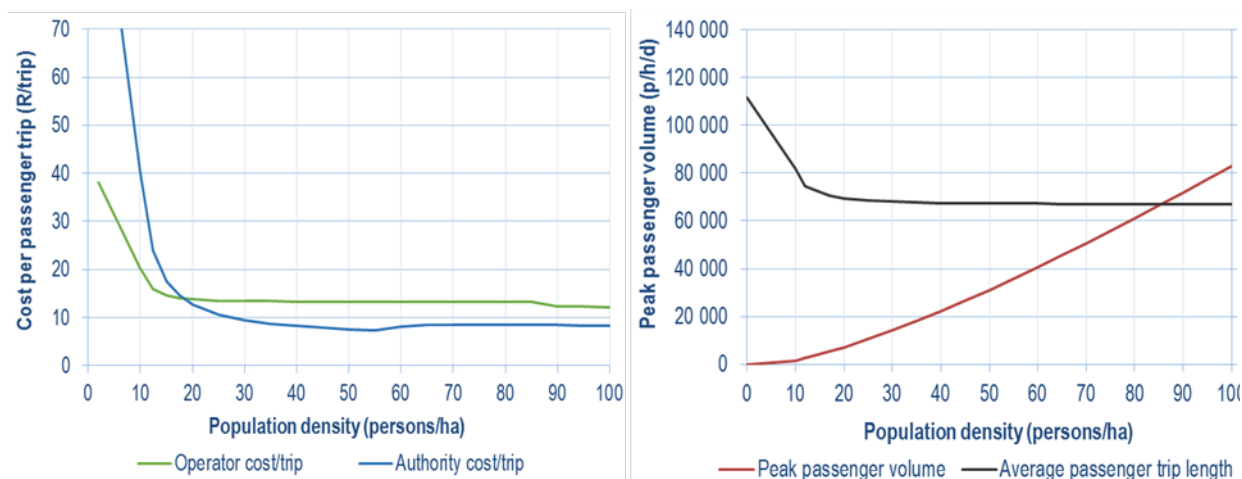
**Figure 2:** *Effect of varying urban density on a 20 km corridor*

Apart from an initial sharp decline in authority cost between two and 20 p/ha, population density does not significantly affect the viability of the BRT system in this case. This contradicts the consensus held by the majority of the relevant literature, challenging the common proposition that achieving high population density targets and thresholds will lead to viable public transport. The contradiction may arise from the fact that, in empirical studies, high density cities also have a generally more supportive land use environment, including high levels of density articulation. Therefore, population density as a determinant is not being analysed in isolation, as it is in this case. An empirical example of unsupportive density, or 'dysfunctional density', is the city of Los Angeles. A relatively high, evenly distributed population density exacerbates congestion and the negative externalities associated with car travel (Un-Habitat, 2013).

A further problem with 'dysfunctional density' is its effect on peak passenger volume. If this representation of a South African transport corridor were to attain the city area gross population density target of Cape Town of 83 p/ha, it would result in a peak passenger volume of 66 377 p/h/d. The observed ridership of the highest capacity BRT systems is significantly below this, at 25 000 – 35 000 p/h/d, even utilising express services (Grey & Behrens, 2013). Therefore, if one of the new BRT corridors resembles the one simulated in this model, the BRT system will reach capacity well before the density target is reached.
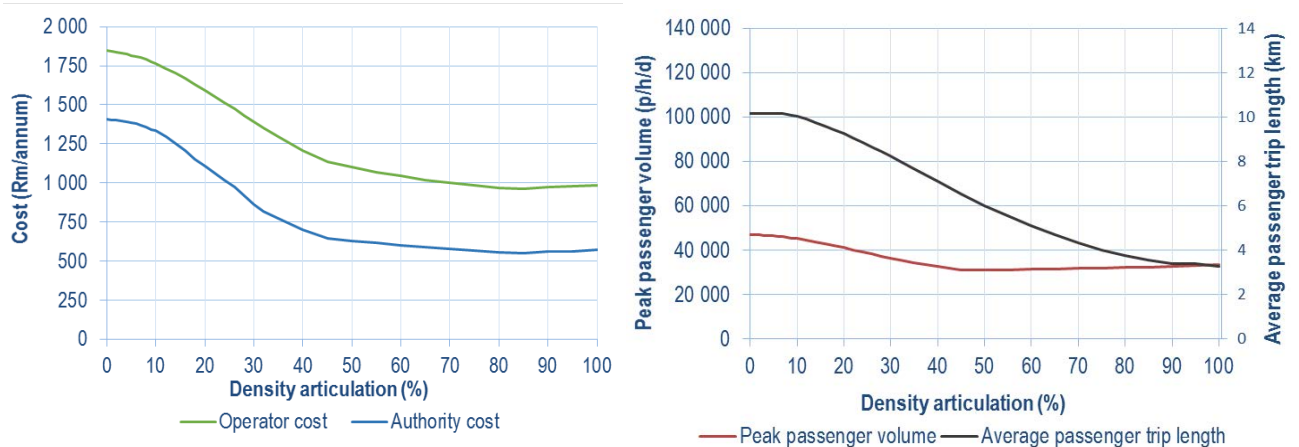
4.2   Density articulation
The density articulation scenario simulations vary the distribution of population while keeping the distribution of other land uses constant. The land uses associated with trip attraction maintain the same distribution pattern as they had in the population density scenario simulations in order to ease comparison and retain the representation of a radial network. Population density was set at 50 p/ha, as density's effect on the system's cost, per user, beyond this value is not significant. Additionally, the peak passenger volume in the population density scenario simulations was 34 889 p/h/d, which is just within the operating capacity of a BRT system.

As of yet, there is no measure for the articulation of density, so one was created by examining the distribution of density across different cities. Curitiba is purported to be an exemplar of high articulated density, owing to its high proportion of residences within walking distance of its trunk service network (Suzuki, Cervero & Iuchi, 2013). In South African cities, the majority poor occupy cheap land at relatively higher densities on the periphery of the city (Maunganidze & Del Mistro, 2012). This would represent low density articulation. The suggested measure for density articulation is the percentage of the urban area's total population that lives within walking distance of the trunk service route, given a specified gross population density. At a percentage of zero, the entire corridor population lives in the blue and beige TAZs of Figure 2, closer to South Africa's current urban situation. At a percentage of 100, no person lives outside of the green TAZs.
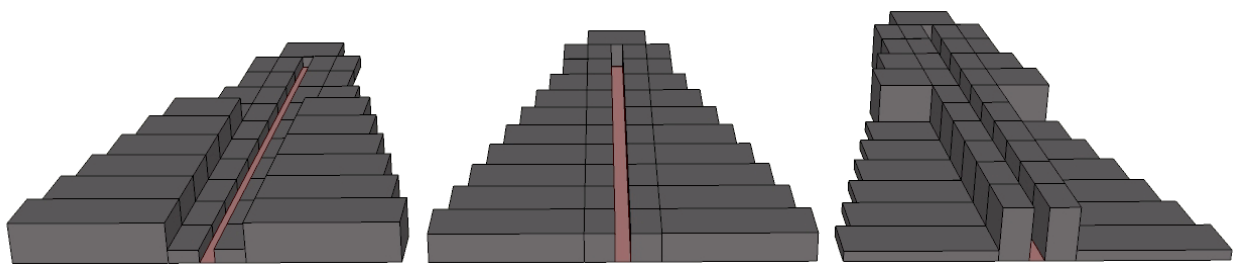
Figure 3: *Orthographic projection of 20%; 43% and 80% density articulation on the simulated corridor representing population density as height*

The concept of density articulation is illustrated in Figure 3, using the generic South African corridor and a gross population density of 50 p/ha. In the centre of the illustration, the density is evenly spread over the catchment area, representing a density articulation of approximately 43%. To the left, a density articulation of 20% is applied, showing that the majority of residences in the TAZs require feeder services. Due to the prevalence of suburban housing and peripheral townships, this situation has a close resemblance to the current South African context. The illustration on the right has an 80% level of density articulation, resulting in a reduced demand for feeder services.

Figure 4: *Effect of varying density articulation on a 20 km corridor at 50 persons/ha*

Figure 4 illustrates the four output analysis indicators for a 20 km trunk corridor at a population density of 50 p/ha. In this scenario, density articulation has a larger effect on authority and operator costs than urban gross population density. The authority cost decreases 59% across the range of density articulation values. As density articulation increases, the reliance on feeder services diminishes until the minimum allowable level is reached. The operator cost decreases in parallel with the authority cost, with increasing levels of density articulation. The decrease in use of the less efficient feeder routes contributes to a 47% drop in the cost borne by operators.

Based on this simulation, the highest possible trunk service walking catchment gross population density that can be achieved is 100 p/ha, well below the public transport trunk corridor density targets of the South African cities presented in Table 1 (which range between 150 and 238 p/ha). To achieve the highest density target (238 p/ha) in this simulation would require a population density of at least 100 p/ha, and result in a peak passenger volume above 100 000 p/h/d, which represents a peak ridership beyond the capacity of BRT systems.

The average passenger trip length decreases by 68% over the range of density articulation. This is important in South Africa, with the prevalence of distance-based fare systems, as the cost per average trip will decrease without changing the fare. The small effect on peak passenger volume is surprising, as the public transport mode share of the trunk-adjacent TAZs rises with increasing density articulation. The initial decrease at low values of density articulation is due to some of the origins of the trips now being closer to the CBD than their destinations and the flow of passengers away from the CBD beginning to rise. The effect of the rising modal split appears to be offset by the increased level of bi-directional flow and more trips terminating in the same TAZ as their origin.

In this corridor simulation, peak passenger volume limits the analysis of density articulation at higher values of population density. The large catchment area of the corridor creates high passenger volumes at low densities. Reducing the corridor length and catchment area could begin to remove this barrier.

4.3 Corridor length

The corridor length scenario simulations halve the dimensions of the corridor to determine to what extent a smaller catchment area can sustain a higher population density and its effect on the transport system's viability. The trunk route length is 10 km and the catchment area is one third of the original. The population density was doubled to 100 p/ha.

As the width of the corridor was reduced in proportion to the decrease in its length, a higher percentage of the total area is now within walking distance of the trunk route. This means that the percentage of the catchment area that requires a feeder service decreases from 56% to 28%. As a result, the effect of leveraging density articulation to increase the gross population density of the trunk service walking catchment TAZs is greatly diminished. This is the reason for the gentler decline in authority cost with increasing levels of articulated density, seen in Figure 5.
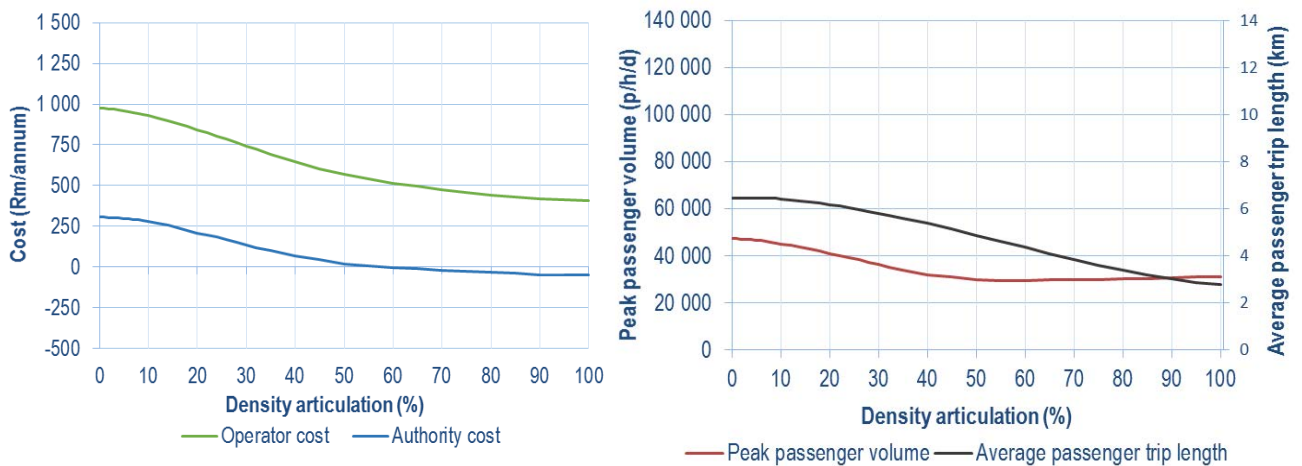
Figure 5: *Effect of varying density articulation on a 10 km corridor at 100 persons/ha*

It is observed that the cost to the authority reaches zero at a density articulation of 60%, after which, the BRT corridor will start to generate a profit. Looking at the worst case of 0% density articulation, the authority cost per passenger trip for the 10 km corridor system is still less than a fifth of that for the 20 km corridor system.

As expected, due to the shorter corridor, the average trip length is much lower than that of the previous scenario simulations. However, it still decreases by 56% to 2.8 km, showing that the magnitude by which it is affected by density articulation is not dependent on its size. Despite the higher population density, the peak passenger volume decreases to within the BRT operating capacity range at 35% density articulation.

South African urbanised city area densification targets are around 80 p/ha, and trunk corridor densification targets are around 200 p/ha (see Table 1). To achieve this disparity in the two figures, even with a catchment area proportional to that of a 30 km corridor, would require a density articulation of at least 70%. This assumes that the policy requirement of 85% coverage is upheld. A service similar to the one described would be unviable and generate demand well above the operating capacity of BRT. For this simulation, the demand generated from a trunk service walking catchment population density of 200 p/ha will fall outside the capacity of a BRT service, utilising density articulation alone. Other land use characteristics, such as land use mix (Bordoloi et al., 2013; Manaugh & Kreider, 2013) and polycentrism (Veneri, 2010; Riguelle, Thomas & Verhetsel, 2007), would also need to be leveraged to optimal levels in order for the peak passenger demand to be met. A fine balance is needed between corridor catchment area, land use characteristics and public transport operating capacity.

5   CONCLUSION

This paper set out to explore the effect of population density and density articulation on the viability of BRT services.

In the population density scenario simulations, very little effect on the viability of the public transport system was observed when all other variables were held constant. This contradicts many of the empirical studies done on the relationship. Unlike this simulation, the corridor catchment areas and density distribution patterns of the comparable cities, in these studies, are not held constant. This attributes some of the effects of corridor length and density articulation to population density. These effects are correlated with population density but not caused by it. Population density as an isolated characteristic seems to be a poor indicator of public transport viability.

Density articulation appears to have a much stronger relationship with public transport viability. Achieving this in South African BRT corridors could substantially improve the future financial viability of services. Small improvements in density articulation could have substantial positive impacts on public transport operations, even at low urban gross population densities. Achieving higher population density would magnify the effect of density articulation even further. However, this is only true for large catchment areas, where density itself is limited by the operational capacity of the public transport service. In smaller catchment areas, where the trunk service walking catchment TAZs make up a majority of the entire corridor, density articulation becomes less effective. This means that the planning and policy focus needs to change, depending on the catchment area of the corridor.

Population density targets could lead to negative impacts on viability if densification occurs in the wrong areas. To achieve a high public transport modal split and sustainable BRT service requires high densities, high articulation, small catchment areas and minimal feeder services. It is suggested that a detailed land use development plan is created for each major public transport corridor, with unique targets for density and density articulation. These plans would need to be integrated with those of the Integrated Rapid Public Transport Network plan and implemented proactively.

There is much research to be done on the relationship between urban form characteristics and public transport viability. This paper has only analysed the effects of manipulating the intensity of residential land use. Further study is required to explore the impact of land use mix on the viability of a public transport service. Further study is also needed to understand relationships between population density articulation and employment density articulation, and to refine and apply empirically the metric for density articulation proposed in this paper.

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