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Framework for integrated planning of bus and paratransit services in Indian cities

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FRAMEWORK FOR INTEGRATED PLANNING OF BUS AND PARATRANSIT SERVICES IN INDIAN CITIES

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Certificate

This is to certify that the thesis entitled, ‘**Framework for integrated planning of bus and paratransit services in Indian cities’** being submitted by **Mr. S B Ravi Gadepalli** to the **Indian Institute of Technology Delhi**, is a record of the bona-fide research work carried out by him under our supervision. The thesis, in our opinion, is worthy of consideration for the award of the degree of **Doctor of Philosophy** in accordance with the regulations of the Institute. The results embodied in the thesis have not been submitted to any other University or Institute for the award of any degree or diploma.

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Abstract

Public transport services in India and many other developing countries are provided by a combination of formal-Government led public transport systems and informal paratransit or Intermediate Public Transport (IPT) systems, which offer shuttle services along high demand corridors with passengers boarding and alighting at multiple points. Despite limited Government support, paratransit systems continue to thrive in many cities serving a crucial shared mobility need of users, without which cities would have more private vehicle usage. Due to their informal nature and the perceived competition to formal public transport systems, they have traditionally been either excluded from the public transport planning processes or designed as a feeder service to the formal transit system. The current thesis recognises paratransit's role in serving end to end travel demand needs, particularly in developing economies with limited public transport supply and not just being a feeder to the formal public transport system. Hence, we develop an integrated planning framework that enables formal and informal public transport systems to operate as complementary systems towards meeting the mobility needs of the city.

We proved an integrated planning framework based on comprehensive understanding of the demand and supply characteristics of both formal and informal systems which currently operate independently to realign services and complement each other. The tactical planning stage of public transport planning i.e. frequency setting was identified as the ideal stage of planning for integration of the two types of services. This will ensure continuity of their existing route networks and at the same time allow for paratransit services' flexibility to switch operations between routes. Visakhapatnam, a representative medium sized Indian city with a significant presence of formal public transport in the form of city bus services and paratransit services provided by three-wheeler

auto-rickshaws with a seating capacity of three to six passengers, was selected as the case city to demonstrate the methodology.

A household survey based data collection and analysis methodology was adopted to analyse the socio-economic and travel demand characteristics of city bus and paratransit users. The variables impacting users' choice between these two systems were derived through binary logistic regression. The high frequency and low occupancy paratransit systems were more popular among shorter trips, while longer trips preferred the fixed table bus systems.

The operational characteristics of bus and paratransit systems were derived through a combination of primary surveys with paratransit operators and secondary data on the city bus operations. Data regarding their network of operation, services offered, passenger demand and revenue generated were collected for analysis. Buses perform a service function in the city by operating throughout the day and on a wider network, while paratransit operates with a profit motive only on high demand corridors and during peak hours. A Data Envelopment Analysis (DEA) based methodology was adopted to compare the performance efficiency of the two systems using a set of input and output indicators that define the performance of the two systems. Paratransit operations were identified to be more efficient compared to buses, due to their demand responsive operations. The lower efficiency of buses was also due to their service obligation to the city to provide affordable services throughout the day, even in areas with low demand.

A bi-level transit assignment and frequency optimisation framework is developed to integrate formal bus and paratransit services. The lower-level of the model solves for the multi-modal transit assignment problem while the upper level solves for the integrated frequency optimisation problem. The transit assignment problem was solved from the users perspective i.e. to minimise their travel time through the user-equilibrium method. The frequency optimisation problem was solved using an integer programming formulation with the objective of minimising operational cost of bus and paratransit systems while meeting constraints like the travel demand on any link

The outputs from the optimisation exercise were used to quantify the impact of the public transport system at various levels i.e. users total travel time spent in the system, operators cost of providing the services and the overall impact on the society by estimating its road space requirement and emissions. Alternative user demand and transit supply scenarios were tested to assess their impacts on the society. The results show significant operational cost benefits of an integrated transit assignment and frequency planning approach where paratransit provides demand responsive services for short distance trips while formal public transport provides fixed schedule services on with broader network coverage.

The analysis established the complimentary role played by bus and paratransit systems in meeting users travel demands. Therefore, it is recommended that cities harness both the systems towards meeting increasing travel needs of developing economies. Formal transit will continue to be the core of the public transport system, providing fixed route services, while paratransit can augment its capacity on high demand corridors and during peak hours. The planning and frequency optimisation framework developed in this thesis can help cities in identifying the modal-mix of fixed route public transport and on-demand services.

सार

भारत और कई अन्य विकासशील देशों में सार्वजनिक परिवहन सेवाएं औपचारिक॰सरकारी नेतृत्व वाली सार्वजनिक परिवहन प्रणालियों और अनौपचारिक पैराट्रांसिट या इंटरमीडिएट पब्लिक ट्रांसपोर्ट .आईपीटी॰ प्रणालियों के संयोजन द्वारा प्रदान की जाती हैं, जो यात्रियों को बोर्डिंग और अलाइटिंग के साथ उच्च मांग वाले गलियारों में शटल सेवा प्रदान करती हैं। अंक। सीमित सरकारी समर्थन के बावजूद, पैराट्रांसिट सिस्टम उपयोगकर्ताओं की एक महत्वपूर्ण साझा गतिशीलता की सेवा करने वाले कई शहरों में पनपना जारी रखता है, जिसके बिना शहरों में अधिक निजी वाहन का उपयोग होता। उनकी अनौपचारिक प्रकृति और औपचारिक सार्वजनिक परिवहन प्रणालियों की कथित प्रतिस्पर्धा के कारण, उन्हें पारंपरिक रूप से सार्वजनिक परिवहन नियोजन प्रक्रियाओं से बाहर रखा गया है या औपचारिक परिवहन प्रणाली के लिए फीडर सेवा के रूप में डिज़ाइन किया गया है। वर्तमान थीसिस यात्रा की अंतिम जरूरतों को पूरा करने में पैराट्रांसिट की भूमिका को पहचानती है, विशेष रूप से सीमित सार्वजनिक परिवहन आपूर्ति के साथ विकासशील अर्थव्यवस्थाओं में और न केवल औपचारिक सार्वजनिक परिवहन प्रणाली के लिए एक फीडर होने के रूप में। इसलिए, हम एक एकीकृत योजना ढांचा विकसित करते हैं जो औपचारिक और अनौपचारिक सार्वजनिक परिवहन प्रणालियों को शहर की गतिशीलता आवश्यकताओं को पूरा करने के लिए पूरक प्रणालियों के रूप में संचालित करने में सक्षम बनाता है।

हमने औपचारिक और अनौपचारिक दोनों प्रणालियों की मांग और आपूर्ति विशेषताओं की व्यापक समझ के आधार पर एक एकीकृत नियोजन ढांचे को साबित किया जो वर्तमान में वास्तविक सेवाओं के लिए स्वतंत्र रूप से काम करते हैं और एक दूसरे के पूरक हैं। सार्वजनिक परिवहन योजना की आवृत्ति नियोजन चरण अर्थात् आवृत्ति सेटिंग को दो प्रकार की सेवाओं के एकीकरण के लिए नियोजन के आदर्श चरण के रूप में पहचाना गया

था। यह उनके मौजूदा मार्ग नेटवर्क की निरंतरता सुनिश्चित करेगा और साथ ही मार्गों के बीच संचालन को बदलने के लिए पैराट्रांसिट सेवाओं के लचीलेपन की अनुमति देगा। विशाखापत्तनम, एक प्रतिनिधि मध्यम आकार का भारतीय शहर, जिसमें तीन से छह यात्रियों के बैठने की क्षमता के साथ थ्री-व्हीलर ऑटो-रिक्शा द्वारा प्रदान की जाने वाली सिटी बस सेवाओं और पैराट्रांसिट सेवाओं के रूप में औपचारिक सार्वजनिक परिवहन की महत्वपूर्ण उपस्थिति थी, कार्यप्रणाली को प्रदर्शित करने के लिए इसे केस सिटी के रूप में चुना गया था।

सिटी बस और पैराट्रांसिट उपयोगकर्ताओं की सामाजिक-आर्थिक और यात्रा मांग विशेषताओं का विश्लेषण करने के लिए एक घरेलू सर्वेक्षण आधारित डेटा संग्रह और विश्लेषण पद्धति को अपनाया गया था। इन दो प्रणालियों के बीच उपयोगकर्ताओं की पसंद को प्रभावित करने वाले चर बाइनरी लॉजिस्टिक रिग्रेशन के माध्यम से प्राप्त किए गए थे। उच्च आवृत्ति और कम ऑक्यूपेंसी पैराट्रांसिट सिस्टम छोटी यात्राओं के बीच अधिक लोकप्रिय थे, जबकि लंबी यात्राएं निश्चित टेबल बस सिस्टम को पसंद करती थीं।

बस और पैराट्रांसिट सिस्टम की परिचालन विशेषताओं को सिटी बस संचालन पर पैराट्रांसिट ऑपरेटरों और माध्यमिक डेटा के साथ प्राथमिक सर्वेक्षण के संयोजन के माध्यम से प्राप्त किया गया था। उनके संचालन के नेटवर्क, सेवाओं की पेशकश, यात्री की मांग और राजस्व के बारे में डेटा विश्लेषण के लिए एकत्र किए गए थे। पूरे दिन और व्यापक नेटवर्क पर बसें शहर में एक सेवा कार्य करती हैं, जबकि पैराट्रांसिट केवल उच्च मांग वाले गलियारों और पीक ऑवर्स के दौरान लाभ के उद्देश्य से संचालित होता है। दो प्रणालियों के प्रदर्शन को परिभाषित करने वाले इनपुट और आउटपुट संकेतकों के एक सेट का उपयोग करके दो प्रणालियों के प्रदर्शन दक्षता की तुलना करने के लिए एक डेटा एनवेलमेंट एनालिसिस (डीईए) आधारित कार्यप्रणाली को अपनाया गया था। पैराट्रांसिट संचालन की पहचान बसों की तुलना में अधिक कुशल होने के कारण की गई थी, क्योंकि उनकी मांग उत्तरदायी परिचालन के कारण थी। कम मांग वाले क्षेत्रों में भी बसों की कम दक्षता शहर में दिन भर में सस्ती सेवाएं प्रदान करने के लिए उनके सेवा दायित्व के कारण थी।

औपचारिक बस और पैराट्रांसिट सेवाओं को एकीकृत करने के लिए एक द्वि-स्तरीय पारगमन असाइनमेंट और आवृत्ति अनुकूलन रूपरेखा विकसित की जाती है। मॉडल का निचला-स्तर बहु-मोडल पारगमन असाइनमेंट

समस्या के लिए हल करता है जबकि ऊपरी स्तर एकीकृत आवृत्ति अनुकूलन समस्या के लिए हल करता है। पारगमन असाइनमेंट की समस्या को उपयोगकर्ताओं के दृष्टिकोण से हल किया गया था, अर्थात् उपयोगकर्ता-संतुलन विधि के माध्यम से अपनी यात्रा के समय को कम करने के लिए। फ़्रीक्वेंसी ऑप्टिमाइज़ेशन समस्या को किसी भी लिंक पर यात्रा की मांग की तरह बाधाओं को पूरा करते हुए बस और पैराट्रांसिट सिस्टम की परिचालन लागत को कम करने के उद्देश्य से पूर्णांक प्रोग्रामिंग फॉर्मूला का उपयोग करके हल किया गया था।

ऑप्टिमाइज़ेशन एक्सरसाइज से आउटपुट का उपयोग विभिन्न स्तरों पर सार्वजनिक परिवहन प्रणाली के प्रभाव को निर्धारित करने के लिए किया गया था अर्थात उपयोगकर्ता सिस्टम में बिताए गए कुल यात्रा समय, ऑपरेटरों को सेवाएं प्रदान करने की लागत और इसके सड़क स्थान की आवश्यकता का आकलन करके समाज पर समग्र प्रभाव और उत्सर्जन। वैकल्पिक उपयोगकर्ता की मांग और पारगमन आपूर्ति परिदृश्यों का समाज पर उनके प्रभावों का आकलन करने के लिए परीक्षण किया गया था। परिणाम एक एकीकृत पारगमन असाइनमेंट और आवृत्ति नियोजन दृष्टिकोण के महत्वपूर्ण परिचालन लागत लाभ दिखाते हैं, जहां पैराट्रांसिट कम दूरी की यात्राओं के लिए उत्तरदायी सेवाएं प्रदान करता है, जबकि औपचारिक सार्वजनिक परिवहन व्यापक नेटवर्क कवरेज के साथ निर्धारित कार्यक्रम सेवाएं प्रदान करता है।

विश्लेषण ने उपयोगकर्ताओं की यात्रा की मांगों को पूरा करने में बस और पैराट्रांसिट सिस्टम द्वारा निभाई गई मानार्थ भूमिका की स्थापना की। इसलिए, यह सिफारिश की जाती है कि शहरों में विकासशील अर्थव्यवस्थाओं की बढ़ती यात्रा आवश्यकताओं को पूरा करने की दिशा में दोनों प्रणालियों का उपयोग किया जाए। औपचारिक पारगमन सार्वजनिक परिवहन प्रणाली का मुख्य हिस्सा बना रहेगा, जो निश्चित मार्ग सेवाएं प्रदान करता है, जबकि पैराट्रांसिट उच्च मांग गलियारों और पीक घंटों के दौरान अपनी क्षमता को बढ़ा सकता है। इस थीसिस में विकसित नियोजन और आवृत्ति अनुकूलन ढांचा निश्चित मार्ग सार्वजनिक परिवहन और ऑन-डिमांड सेवाओं के मॉडल-मिश्रण की पहचान करने में शहरों की मदद कर सकता है।

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1 Introduction

1.1 Urban mobility scenario in developing countries - Role of paratransit systems

Urban transport systems in developing countries are characterised by low-vehicle ownership rates and high dependence on public transport systems for daily commute to fulfil various activities. The city Governments typically provide formal bus or rail based public transport services like city buses, Bus Rapid Transit (BRT), sub-urban rail or metro rail systems. In most cases the available capacity and pace of development of these formal public transport systems is inadequate to handle the increasing travel demands of the users (Cervero (2000), Phun and Yai, 2016). This led to the emergence of informal public transport systems which are owned and operated privately. Typically known as Intermediate Public Transport (IPT) or paratransit systems, they provide shared transport services between important origins and destinations in cities with unmet public transport demand. In the developed world paratransit services are often associated with demand-responsive 'dial-a-ride' systems provided for persons with disabilities. In the developing world paratransit services are usually provided at a far larger scale for the general population, often by unregulated or illegal operators within the informal sector. These services are normally individually owned and operated and unlike formal public transport, do not follow a fixed route network, frequency and timetables (Ferro and Behrens, 2013). They operate along a few high demand corridors with adequate flexibility to switch between routes and destinations according to the user demand. These services typically operate as an independent system and may not necessarily be designed or operated as a feeder to the formal public transport system.

While both formal transit and paratransit services operate with the common objective of providing shared mobility services to people, in most cases the paratransit services operate independently with limited integration within the city's governance, policies and planning processes (Ferro and Behrens, 2015). This further leads to multi-fold problems like lack of regulatory clarity on the role of paratransit system as a form of public transport, lack of complementarity between formal transit and paratransit systems i.e. concentration of both the operations along high-demand corridors while many areas remain underserved, increased congestion on roads created by oversupply of competing services, poor air quality due to emissions from ill-maintained paratransit vehicles. Therefore, the need for greater integration between these modes has been highlighted by many successive studies (Cervero and Golub, 2007, Ferro and Behrens, 2013, Phun and Yai, 2016). As detailed further in the international literature review section, majority of the research on paratransit systems focusses on means for their institutional and regulatory integration into the transport governance of the city. The operational aspects of competing public and paratransit systems and their relative performance received limited attention.

1.2 Urban mobility scenario in India

India's urban population is projected to increase from 377 million in 2011 to approximately 600 million by 2030 (UN, 2015). We currently have approximately 468 cities with a population of more than 100,000 inhabitants (Census, 2012b). The sustainable development of these cities depends on developing safe and low carbon transport systems to meet citizens' needs for access to the required goods, services and activities. Many small and medium sized Indian cities are still low on per-capita incomes and vehicle ownership rates compared to many developed and developing economies. As a result, usage of personalised cars and two-wheelers is still prohibitively expensive for large sections of the society, which are still reliant on public modes of transport (Census, 2012a).

Table 1 provides an overview of the mode shares of work trips in Indian cities of various population categories. Since the census of India database doesn't provide mode share information for cities with less than one million inhabitants, the mode share database provided in Moser et al. (2016) is presented in Table 2. This covers the mode share data of 27 Indian cities across population and trip purpose categories aggregated from their Comprehensive Mobility Plans (CMP). Both the databases point to walk being the dominant mode of transport across cities, followed by two-wheelers. Among shared modes of transport, bus and three-wheelers are the most used modes, while rail based modes have a significant share only in the metropolitan cities. The comparision across city sizes and trip purposes presented in Table 2 highlights the relative shares of buses and three-wheelers across cities. Buses cater to a significantly higher share of trips in the metropolitan cities, while informal shared services offered by three-wheelers dominate the shared mobility trips in the smaller cities. However, in the small and medium sized cities i.e. cities with population less than 10 million, the mode shares of bus systems decrease while the mode shares of paratransit modes like three-wheelers is equivalent to or more than the formal bus systems. As the city size reduces it is also observed that the proportion of two-wheeler trips increase. This shows the inadequacy of the combined public transport services provided by the formal and informal systems.

Table 1 Mode Shares for work trips in Indian cities

Population Category	**>5 million**	**2–5 million**	**1–2 million**
Bus	23	6	12
Three-wheeler	4	9	5
Rail/ Metro	9	2	2
Car	9	5	5

Two-Wheeler	20	30	27
Cycle	9	21	21
Walk	27	26	27
Total	100	100	100

(Source: (Census, 2012a))

Table 2 Mode Shares of Indian cities across trip purposes

Population Category	**>10 million**	**1-10 million**	**<1 million**
Bus	20	13	4
Three-wheeler	3	11	13
Rail/ Metro	14	2	0
Car	6	3	2
Two-Wheeler	9	23	27
Cycle	5	13	6
Walk	43	37	49
Total	100	100	100

Source: (Moser et al., 2016)

While the current share of sustainable modes of transport like walk and public transport are high, serious backlogs exist in urban transport infrastructure and services provided in most cities. Only 67 Indian cities have access to a formal public transport system. Lack of efficient public transport and its access infrastructure, combined with increasing incomes is leading users to shift to alternatives means of mobility including increased use of private vehicles. As a result, urban mobility systems in India are contributing to the deterioration of air quality, reduced traffic safety and increasing congestion on roads (Pucher et al., 2005, Wilbursmith, 2008, Guttikunda et al., 2014).

Various policy initiatives of the Government of India (GoI) have provided recommendations on the urban development, transport planning and infrastructure supply solutions to address the challenges of urban growth. These include: the National Urban Transport Policy (MoUD, 2006), National Transport Development Policy , Twelfth Five Year Plan (MoUD, 2012b) , National Mission on Sustainable Habitats (MoUD, 2011) and the High Powered Expert Committee report on Indian urban infrastructure and services (HPEC, 2011). One of the key recommendations that was emphasised in all the policies is to provide a good quality public transport system in the cities. An efficient public transport system helps in meeting the mobility needs of a city using fewer financial and energy resources compared to a private vehicle oriented mobility. It also helps in improving the public health and wellbeing of the inhabitants by reducing pollution and improving safety on roads (Census, 2011b, Woodcock et al., 2009).

In line with the policy recommendations, the Ministry of Urban Development (MoUD) of the Government of India has identified improving public transport infrastructure and services as a priority and made investments across the country through the Jawaharlal Nehru Urban Renewal Mission (JNNURM) between 2007 and 2014 (MoUD, 2012a). These efforts are being continued through the ongoing urban development missions like the Atal Mission for Rejuvenation and Urban Transformation (AMRUT) and the Smart Cities mission (MoHUA, 2018). The investments in public transport included funding to augment or introduce bus fleets and to develop mass rapid transit systems like Bus Rapid Transit System (BRTS) and Metro rail systems across the country. Even after these efforts, only 67 cities in the country have formal city bus systems. While 49 cities augmented their bus services while 12 cities introduced bus services for the first time over the past decade, with partial financial assistance from the Government of India's (GoI). 11 of these cities have also taken up BRT systems and 6 cities have taken up metro systems funded partially or totally by the Government (MoUD, 2013). The efforts of Government of India are similar to other developing countries in Latin America and Africa that tried to build formal transit systems in order to improve the public transport systems in cities (Ferro and Behrens, 2013, Ferro and Behrens, 2015).

However, such simplistic top down approach of adding city bus fleet or BRT corridors to cities does not necessarily match well with the mobility needs and existing transport systems in cities. The bus fleet sanctioned by Government of India were decided based on the population of the city without considering any other mobility or development characteristics of the city like it's area, population density, travel demand patterns etc. Additionally, the government's definition of "public transport" is restricted to bus and rail based systems and doesn't consider localised and informal tranport services like shared auto-rickshaws, maxi cabs, mini buses etc. In this context, the following sections present an overview of the existing bus and paratransit systems in Indian cities.

1.2.1 City bus systems in Indian cities

Bus based public transport systems in India are traditionally provided by State Transport Undertakings (STUs) formed under the Road Transport Corporations (RTC) Act 1950 (GoI, 1950). More recently, many cities have set up Special Purpose Vehicles (SPVs) to provide city bus services under Public Private Partnerships (PPP). In both cases, a Government agency in the city is in charge of the policy and planning of the bus systems. In many cities, the operations of these services are also carried out by the Government agencies, while a few cities outsource their services to private operators.

The operational characteristics of eight of the most populated Indian cities were reviewed to understand their existing performance. Figure 1 presents a few key indicators of their performance:

- Total fleet size, to understand their overall capacity
- Percentage schedule adherence, to understand their punctuality
- Passengers carried per bus per day that indicates the efficiency of each bus and
- Total passengers carried, to indicate their overall contribution to the city

All the seven cities represented in the chart have a population of more than 5 million inhabitants. However, the total bus fleet operating in these cities varies significantly, with Bangalore having the maximum fleet among all the cities, while Kolkata has the least. The schedule adherence was maintained at similar levels in most cities, except Ahmedabad, which showed a significant improvement. Most of the cities cater to more than 600 passengers per bus per day, which is high compared to International standards (UITP, 2017). Chennai has more than 1200 passengers per bus indicating a heavily loaded system with inadequate fleet. Delhi, Mumbai, Chennai and Mumbai carry more than 1 billion passenger trips per year, which indicates the huge number of people dependent on their services.

However, the performance of the city bus systems hasn’t improved significantly in any of the cities to match the passenger demands. The fleet size and passengers carried have been declining in most of the cities. Such decline in capacity and ridership was observed despite these cities witnessing an increase in population and economic activity indicates an urgent need for improvement of these systems. Also, this decline in performance, in spite of the Government of

India’s stated policy goal of improving formal public transport systems, highlights the need to improve the current efforts towards improving bus systems.

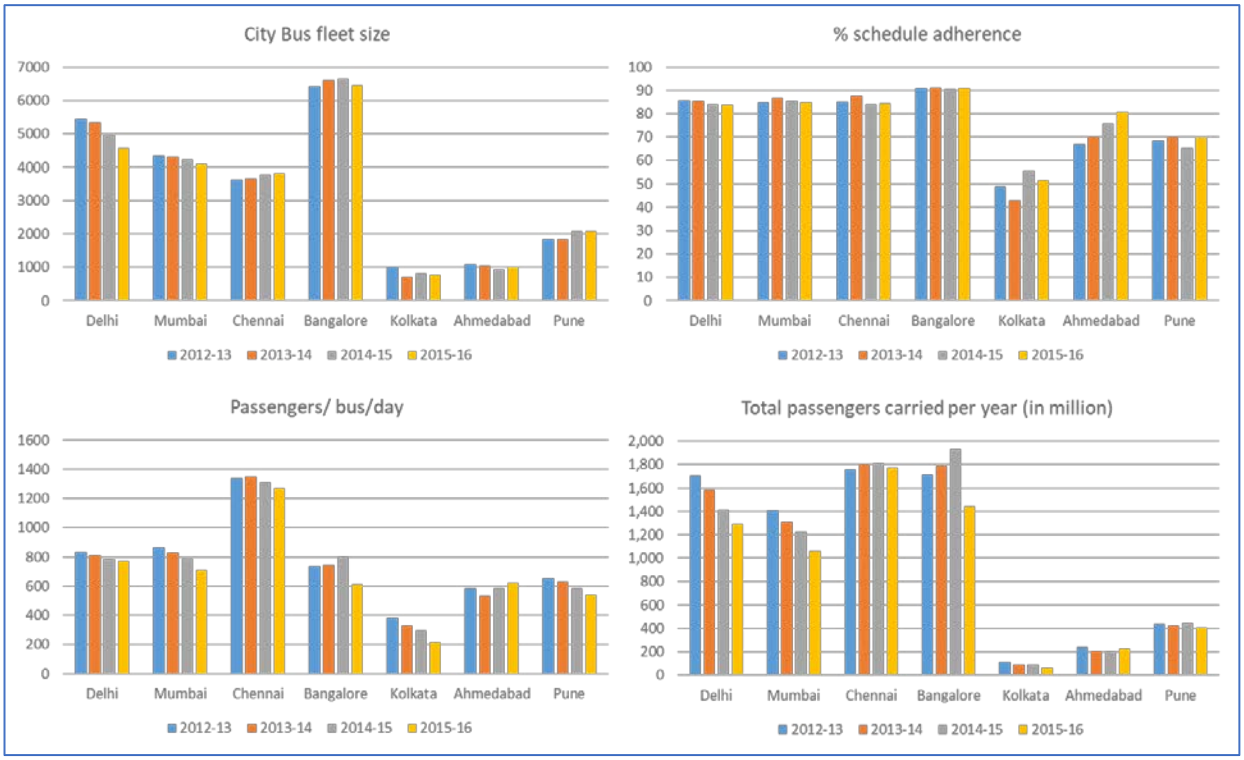


Figure 1 Performance of city bus systems in India

Source: (MoRTH, 2017a)

1.2.2 Paratransit in Indian cities

The term “paratransit” conventionally describes a flexible mode of shared passenger transportation that does not necessarily follow fixed routes or schedules. . However, the following variations in paratransit defnitions are observed in literature

i) In developed countries paratransit services are often associated with demand-responsive ‘dial-a-ride’ systems provided for individuals with mobility challenges including elderly and people with a disability (Dikas and Minis, 2014)

ii) In the developing world paratransit services are usually provided at a far larger scale for the general population, often by unregulated or illegal operators within the informal sector. For this reason, paratransit in the global south is sometimes also referred to in the literature as “informal” transport. In cities where the formal systems are absent or have inadequate capacity, these informal modes operate as paratransit, also known as an Intermediate Public Transport (IPT), providing unscheduled but high frequency services along high demand corridors. Paratransit services are provided by a wide-range of vehicle types such as three-wheelers with small capacity to vans, tempos and even mini-buses (Ferro and Behrens, 2013)

Table 1 and Table 2 show the significant mode share of three-wheelers which provide paratransit services in small and medium sized Indian cities, with limited access to formal public transport (Ferro et al., 2012). Depending on the size and transport characteristics of a city, paratransit modes operate in two broad categories: (a) taxi (point to point) services, which are flexible demand-based services in which the passenger determines the destination, and (b) informal public transport (bus-like) services characterized by shared fixed-route services with intermediate stops for boarding and alighting. The license for operation of each vehicle is issued by the Road Transport Authority (RTA) of each city on an annual basis, for each vehicle to operate as a ‘contract carriage’ i.e. as a taxi service for end to end trips (Badami and Haider, 2007). However, a soft enforcement regime allows them to operate as a ‘stage carrier’ i.e. as a shared mode of transport operating as a shuttle service along fixed routes (Mani et al., 2012a, IUT, 2014). Each paratransit vehicle operates independently with limited coordination with the remaining operators. Therefore, their day to day operations are not monitored by any designated Government or private agency. By virtue of being individually owned and operated, their services are more demand responsive compared to the formal bus systems.

Figure 2 shows the proportions of various shared modes of transport per-capita i.e. the share of bus, taxi and paratransit vehicles registered per person in various cities for the year 2015 (MoRTH, 2017b). In most cities, the paratransit share of vehicles per-capita is much higher than the bus and taxi numbers. While it is acknowledged that the actual service offered by these vehicles depends on their capacity and operational characteristics, the number of vehicles registered is a good indicator of the market demand for these vehicles. The high share of paratransit vehicles in most cities underlines their important role in meeting the public transport demand in cities. While paratransit caters to a significant proportion of trips in cities, even greater than the city bus system in many cases, being privately managed and informal in nature has traditionally excluded them from the formal transit policy and planning processes (Wilbursmith, 2008). This has led to the formal and informal systems operating in silos and competing with each other, rather than synergising to meet the larger societal objective of maximising transit services in the city.

An integrated public transport system in a city would require the bus and paratransit systems in a city to integrate their operations such that they complement each other and deliver a wider network of services. Therefore it is important for cities to acknowledge the role of paratransit systems and include into the planning processes for their public transport systems.

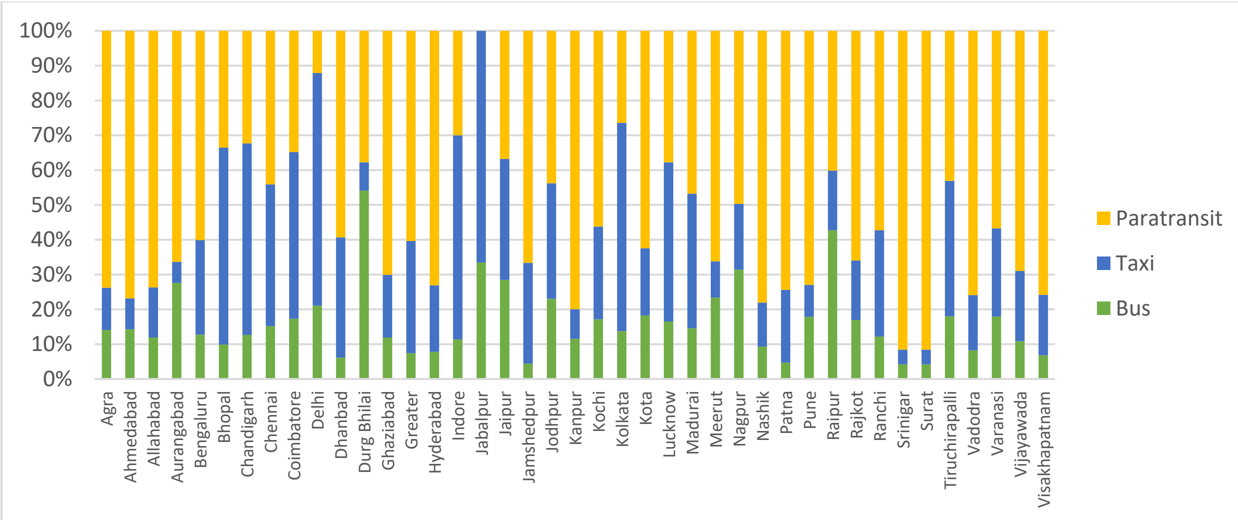


Figure 2 Proportion of per-capita shared transport vehicles in Indian cities
(Source:(MoRTH, 2017b))

1.3 Need for the current study

The previous sections highlight how the Government sanctioned formal public transport is witnessing a decline in capacity and performance while paratransit, which forms the mainstay of shared mobility is being neglected in the policy and planning practices. As a result, the overall attractiveness of formal and informal public transport services is on the decline and many Indian cities are witnessing a significant increase in users shifting to personal modes of transport, like cars and two-wheelers, further leading to externalities like increased congestion, poor air-quality (Guttikunda et al., 2014).

In addition to the local challenges faced by Indian cities, global research on Sustainable Development Goals (SDGs), new urbanism and climate-change mitigation initiatives point towards the need to retain and enhance public transport usage in Cities (UITP, 2017, UNDP, 2015). Emerging economies like China, India and African countries have a significant role in addressing these global challenges given their higher share of growth rate in urban population. Therefore, a detailed analysis of the current gaps in public transport systems in India can also inform other developing countries in improving their own systems. A framework for integrating market driven initiatives like paratransit into the formal public transport planning processes can help these countries in meeting their urban mobility challenges efficiently.

A framework for integrating formal and informal services will require a comprehensive understanding of the two key stakeholders of these systems i.e. its users and service providers. In this context, the current thesis developed a methodology for a comprehensive analysis of the comparative travel behaviour of users and performance characteristics of both the systems. The demand and supply characteristics of the two systems were used to develop an integrated frequency optimisation model that determines the optimal frequency and fleet requirements of the systems for the overall public transport demand. The methodology was demonstrated for the case of a medium sized Indian city, with significant presence of formal and informal systems. The frequency optimisation model was applied to test the impact of alternative scenarios of bus and paratransit systems for the case city.

The following sections provide a summary of the state of the art literature on integrating public and paratransit services, followed by the methodology adopted for the current study, the details of data collection, analysis and the findings.

1.4 Aim and Objectives of the thesis

The aim of this thesis is to develop an integrated service planning framework for public transport and paratransit systems in Indian cities that incorporates the distinctive characteristics of users and operators of the two systems and optimises their frequency and fleet requirements

1.4.1 Objectives of the thesis

The following are the specific objectives to be met towards achieving the aim of the thesis

i. Comparing the socio-economic and travel demand characteristics of public transport and paratransit users
ii. Establishing the relative operational characteristics and performance efficiency of public transport and paratransit systems
iii. Developing a multi-modal framework to optimise frequency and fleet requirements of each mode by balancing users' travel needs with operators' cost considerations
iv. Analysing alternative demand and supply scenarios to quantify the impacts of alternative public transport development scenarios in a city and recommending a way forward for integrated public transport improvement

1.5 Organisation of the thesis

This thesis is organised into a total of seven chapters. **Chapter 1** is the introduction chapter, followed by literature review in **Chapter 2**. This includes a detailed review of the state of the art literature on the key focus areas of the study i.e. literature on travel behaviour research of public transport and paratransit users, performance efficiency measurement and benchmarking of public transport systems, previous approaches for formal public transport and paratransit service integration and finally literature on transit network frequency setting problem and transit flow assignment. **Chapter 3** explains the methodology adopted in this study including data collection, comparative analysis of user characteristics and operational efficiency of bus and paratransit services followed by the integrated travel demand modelling and frequency optimisation. **Chapter 4** focusses on the case city selection to apply the adopted methodology and a detailed description of the data collected for various components of the thesis. The analysis of user characteristics and operational performance is presented in **Chapter 5** along with the key findings on the relative roles of bus and paratransit systems. **Chapter 6** details out the integrated transit assignment and frequency optimisation model developed for the case city. Results for the model are presented for the current operations in the city along with alternative scenarios of bus and paratransit integration and their societal impact. **Chapter 7** presents the key conclusions derived from the various components of the study i.e. findings from user characteristics analysis, operational performance evaluation, integrated modelling of the two systems and the key findings from the scenario analysis. The chapter also highlights the key research contributions of this thesis and scope for future studies to build on the research carried out in this thesis.

2 Literature review

Published research papers and reports have been reviewed to understand the current approaches being adopted to solve for the objectives identified for this thesis. The findings from the reviewed literature are grouped into the following thematic areas of research:

i) Analysing travel behaviour of formal public transport and paratransit modes

ii) Evaluating performance efficiency of formal transit and paratransit systems

iii) Integrating both the systems such that their service supply is optimised by balancing users and operators

2.1 Analysing travel behavior of formal public transport and paratransit users

Literature review focussed on the methods to collect and analyse data for a comprehensive understanding of the travel behaviour of formal public transport and paratransit users and their relevance to understand paratransit user behaviour at the city level.

2.1.1 Travel behaviour research on public transport users in Indian cities

Previous research on public transport in India focussed majorly on establishing their important role in meeting the increasing demands for mobility, supporting the economic development and environmental sustainability of cities and the need to improve its capacity and efficiency. Tiwari (2002) and Pucher et al. (2005) present the current mode choice behaviour of users across various Indian cities. Both the articles highlight that the low income and vehicle ownership levels have led to public transport, walk and cycle being the most preferred travel options for users. However, lack of adequate policy focus and infrastructure creation to retain current mode shares is leading to increased ownership and usage of private vehicles, further resulting in a reduction in public transport patronage across cities (Badami and Haider, 2007).

City-level analysis of the public transport mode choice behaviour in India received limited research attention as captured here. Suman et al. (2016) present the mode choice behaviour of bus commuters in New Delhi and establish the declining bus patronage with due to increase in personal income and vehicle ownership patterns. Suman et al. (2017) compare the travel characteristics between mode choice behaviour of bus commuters in Delhi and Mumbai. Overcrowding of buses was identified as a major reason for declining bus commuters in both the cities, followed by inadequate reliability, comfort and travel time. Similarly, Vedagiri and Arasan (2009) developed mode choice models for user preference between buses and paratransit in Chennai and identified travel time as the key variable impacting mode choice. Analysis by Srinivasan and Bhargavi (2007) for Chennai also revealed that declining bus ridership can also be because of factors external to bus system like growing vehicle ownership and poor congestion management in the city. Deb and Filippini (2010) have analysed public transport demand variations of twenty-two Indian cities between 1990 and 2001. The analysis highlighted service quality, social and demographic characteristics are important variables to determine bus demand while the impact of fares wasn't significant. Goel and Tiwari (2015) and Rastogi and Krishna Rao (2003) studied the characteristics of access and egress trips made by rail based mass-transit users in Delhi and Mumbai respectively. Both the articles establish the travel characteristics of users in accessing mass transit modes.

In summary, literature on public transport mode choice behaviour in India is limited and has traditionally focussed on formal public transport modes like bus, metro and sub-urban rails. The demand patterns of informal public transport services which are ubiquitous across India and the comparative mode-choice behaviour of their users has not been presented in any of these articles. Furthermore, most of the existing public transport research in India was focused on large cities with population more than 5 million (iTrans, 2012). India has 468 cities with population in the range of 100,000 to 5 million inhabitants, where the user characteristics and their mobility needs vary significantly compared to the larger cities (Census, 2011b). However, little research exists regarding the public transport users in such cities. The emphasis on an integrated analysis of formal public transport and paratransit user characteristics has been limited. The lack of understanding of the relative commuter preferences of these modes is a key barrier towards planning for an integrated system.

2.1.2 International review of public transport user behaviour analysis

The topic of travel behaviour research and mode-choice of individuals using formal public transport and private transport modes has been covered extensively in literature. The data for travel behaviour and mode choice analysis of users is typically captured through Revealed Preference (RP) surveys to understand preferences about existing modes of transport and through Stated Preference (SP) surveys in the context of a proposed new mode of travel. The source and scale of data used to derive these models varies across studies.

Stopher and Greaves (2007) compared alternative data collection methods explained above. They identified household survey based activity and travel diary collection to be capturing the most detailed and accurate information compared to alternatives like panel survey of existing users, telephonic and internet based surveys. Face to face interview based surveys also suit better in low-income countries like India where the penetration of technology is relatively low, therefore hampering internet, phone or mobile application based surveys.

The most popular method for analysing the travel behaviour and mode choice data across multiple modes are discrete choice models, particularly the Multinomial Logit (MNL) models. The MNL models are based on disaggregated data of individuals using various modes. This includes socio-economic characteristics like age, gender, income and vehicle ownership and travel characteristics like trip purpose, distance, travel time and perception towards shifting between different modes. In case of public transport trips, the travel-specific parameters typically include detailed breakup of the trips including access to the transit stop, waiting time, in-vehicle trip time and egress trip time i.e. from the alighting stop to the final destination. In case of only two competing modes, a binary logit model may be adopted (Koppelman and Bhat, 2006). The applications of these methods to understand public transport user behaviour are summarised below.

Hensher and Rose (2007) used a Stated Preference (SP) based household survey approach to parameterise mode choice models for commuting and non-commuting travel patterns in Sydney in the context of a new public transport infrastructure. Nested logit models were developed to establish mode choice behaviour of transit users and non-users in the city. Access and wait times of users were identified to be the mode specific attributes significantly influencing the mode choice of public transport while gender and income are the socio-economic attributes with significant influence. (Idris et al., 2014) use a combined Revealed Preference (RP) and SP questionnaire survey of daily commute travellers to study the role of service attributes in determining users' mode choice behaviour in Toronto. A web-based panel survey of 3,769 commuters was adopted for data collection. The article concludes that Level of Service (LOS) attributes like waiting time, system reliability, number of transfers and crowding level of the system are of more importance to user compared to travel cost and in-vehicle travel time. Imaz et al. (2015) used the same data to model the key attributes impacting customers' loyalty to public transport using a binary logit model to compare transit users and non-users. Service quality and reliability were identified as the main drivers of public transport customer loyalty. Particularly, transit users were observed to be sensitive to the level of crowding of the transit vehicles, as well as to travel and wait times. Van Lierop and El-Geneidy (2016) also modelled transit customer loyalty based on service quality perception of three categories of users i.e. captive users, non-captive users and captive by choice users (users who can afford a car but don’t own one). Five years of customer satisfaction survey data of 11,938 transit users in Montreal was modelled to measure user behaviour for the following attributes: Service quality of bus and train, reliability, safety, information and cleanliness. Captive users' satisfactions with transit services more influenced by safety of the service while quality of information was more important to choice and captive by choice users. Reliability of services were more significant for mode choice compared to the planed frequency.

Dell’Olio et al. (2010), Dell’Olio et al. (2011) used a commuter survey based approach to study users’ perception of transit service quality before and after providing them with information of the attributes of their system. A sample survey comprising of RP and SP questionnaire was carried out on board buses in the city of Santander revealed waiting time, cleanliness and comfort as the variables that define the quality desired from a city bus system. Nor et al. (2006) carried out SP surveys on-board public transport services in the city of Putrajaya, Malaysia to identify measures to improve transit ridership in the city. MNL models were used to establish users’ travel preferences. Improvements in transit service quality was identified as one of the key measures to improve demand but external measures like congestion and parking price were identified as more important. Basuki Joewono and Kubota (2008) carried out on-board surveys of 980 paratransit users in Bandung, Indonesia to understand users’ satisfaction with the paratransit operations. The article establishes the key service attributes like accessibility, reliability and convenience offered by paratransit services as the key reason for their current demand. However, retaining their low fares was identified as the most important attribute to retain and increase their users. Weng et al. (2018) analysed the mode choice behaviour between bus and rail transit users in Beijing. A combination of online surveys and in-person interviews at transit stops was used to collect data of

708 users including 369 bus and 339 rail transit users. A binary logit model was developed to analyse the mode choice behaviour and was validated using smart card data of existing users. Gender and travel time were observed to be the variables with the highest correlation with mode choice between bus and rail based transit.

Kuhnimhof et al. (2012) adopted a combination of secondary data sources to study the trends of public transport usage among various categories of users in Germany. The National household Travel Surveys (NTS), Income and Expenditure Surveys (EVS) along with articles providing time-series data on mode shares were used to establish decreasing car usage among young adults in Germany and increasing multi-modality in trip patterns. Similarly, (Molnar and Mesheim (2010), Kuhnimhof et al., 2012) used the National Transport Study (NTS) in Britain to derive Multinomial Logit (MNL) models for public transport mode-choice behaviour. The article identified age and gender as key factors in mode choice as younger males in Germany have more multimodality and lesser car ownership and usage.

The summary of the literature on travel behaviour analysis of public transport users is summarised in Table 3.

Table 3 Summary of international literature on public transport mode choice behaviour

Authors	Objectives	Data used	Modelling approach	Key findings	Location
(Nor et al., 2006)	Identifying measures to improve transit ridership in Putrajaya	Stated Preference (SP) survey of 1,943 individuals	Multi-Nomial Logit (MNL)	• Improving service quality may only lead to 20-25% improvement in transit ridership. • Demand restriction measures like cordon pricing and parking charges have a larger potential to increase transit demand	Putrajaya, Malaysia
(Hensher and Rose, 2007)	Estimating demand for a new transit mode	Household surveys for Stated Preference (SP) data of 453 individuals	Nested logit model	• RP data recommended only to establish current case • SP & nested logit models should be used for demand prediction • Access and wait times among mode specific attributes, gender and income among socio-economic attributes were the attributes influencing public transport mode choice	Sydney
(Basuki Joewono and Kubota, 2008)	Measuring user satisfaction with paratransit services	980 on-board surveys covering service quality and general information	MNL	• Service quality attributes like accessibility, reliability and convenience of paratransit users have resulted in current demand. • However, retaining current fares is key to retain current mode share	Bandung, Indonesia

(Dell'Olio et al., 2010)	Study users' perception of transit service quality before and after providing them with information of the attributes of their system	RP+ SP survey of 768 users at bus stops and throughout the city	MNL	Wait time, cleanliness and comfort are the variables that define the quality of service	Santander, Spain
(Dell'Olio et al., 2011)	Variables impacting mode choice of current and potential users	RP + SP surveys-On board and bus stop surveys	MNL	Wait time, journey time and level of occupancy most important to potential users	Santander, Spain
(Kuhnimhof et al., 2012)	Trends of public transport usage among various categories of users in Germany	Secondary data from National household Travel Surveys (NTS), Income and Expenditure Surveys along with other time-series data on mode shares	Multi-level regression	Age and Gender are key factors in mode choice as younger males in Germany have more multimodality and lesser car ownership and usage	Germany (multiple cities)
(Idris et al., 2014)	Identifying key transit attributes affecting mode shift towards public transport	Web based survey of 1,211 shortlisted for using RP+SP questionnaire in Toronto	MNL	• Travel cost, time and socio-economic variables affect mode choice behaviour • Additionally, Level of Service (LOS) attributes like wait time, reliability, number of transfers, transit technology and crowding level are also significant	Toronto
(Imaz et al., 2015)	Key attributes impacting loyalty of customers	RP+SP data from (Idris et al., 2014)	Binary logit for transit users and non-users	• Service quality and reliability attributes are the main drivers of public transportation customer loyalty • Transit users are particularly sensitive to the level of crowding of the transit vehicles, as well as to travel and wait times	Toronto

(Van Lierop and El-Geneidy, 2016)	Influence of transit users' perceptions of service quality and user satisfaction on loyalty of various user groups i.e. captive public transport users, non-captive users and captive by choices users i.e. one's who can afford a vehicle but don't own it.	Five years of customer satisfaction questionnaires between 2009 and 2013 collected by two Canadian transit providers of 11,938 transit customers in total	Structural Equation Modelling	• The user behaviour is measured using the following attributes: Service quality of bus and train, reliability, safety, information and cleanliness • Captive users' satisfactions with transit services more influenced by safety and less by quality of information which is important to choice and captive by choice users. • Reliability more significant for mode choice compared to frequency	Montreal
(Weng et al., 2018)	Analysing mode choice behaviour of public transport users in Beijing	RP and SP surveys for disaggregated binary logit model+ smart card data for model validation. Online survey and manual survey at transit stops of 708 users including 369 bus and 339 rail transit users.	Binary logit	• Gender and travel time are the variables with the highest correlation with mode choice between bus and rail based transit	Beijing

2.1.3 Summary of public transport travel behaviour

The topic of travel behaviour research and mode-choice of individuals using formal public transport and private transport modes has been covered extensively in literature (Idris et al., 2014, Dell'Olio et al., 2010, Hensher and Rose, 2007, Kuhnimhof et al., 2012). However, literature on travel characteristics and mode choice behaviour of paratransit users is limited to studies which used sample surveys of existing paratransit users to understand their travel behaviour (Basuki Joewono and Kubota, 2008, Yaakub and Napiah, 2011). We couldn't find any literature comparing the mode choice behaviour between formal public transport and paratransit service users.

The key findings from the literature presented above is that public transport mode choice behaviour is typically dependant on the personal or socio-economic characteristics of users like age, income etc. and their travel characteristics like travel time, trip length, wait-time etc. The travel characteristics of users are further dependent on transit service quality attributes like frequency, reliability, cleanliness and comfort. The data to understand public transport user behaviour can based on RP survey of existing commuters, SP survey of existing and potential commuters, a combination of RP and SP surveys and even based on secondary data sources. This data is typically collected either though household surveys, on-board and off-board surveys either online or in-person. Multinomial and binomial logistic regression based methods were typically adopted to predict choice behaviour and its correlation with various attributes of individuals.

Public transport user behaviour in the Indian context have been limited to a few studies (Suman et al., 2016) (Massimo and Kaushik, 2010) (Vedagiri and Arasan, 2009) (Srinivasan and Bhargavi, 2007). These studies have focussed on analysing user choice behaviour towards public transport modes in Indian cities. Various socio-economic and travel attributes of users that determine their mode choice behaviour were established. However, these studies focussed predominantly on formal transit modes like bus and rail based systems, present in metropolitan cities. Research on informal transport services in India is limited to a few which provide a macroscopic overview of the urban transport sector in India studies (Pucher et al., 2005) (Singh, 2005) (Mani et al., 2012b). The emerging vehicular and passenger modal share trends across Indian cities are analysed to propose the policy roadmap required to incorporate paratransit into the sustainable transport development paradigm in India. The travel behaviour analysis of paratransit users in small and medium sized cities hasn't received much attention.

The current thesis will address the gaps in literature by using detailed household survey data to establish the detailed socio-economic and travel characteristics of paratransit users and how they compare with formal public transport users. Further, the variables that show significant correlation with their mode choice behaviour between the two modes will also established.

2.2 Evaluating performance efficiency of formal transit and paratransit systems

Efficiency represents the performance of an organization or a service by the amount of output produced for a given amount of input (energy, time, money). Efficiency evaluation of a service enterprise depends on how well the service is managed, how well that is received and how big the organization is (Sherman and Zhu, 2006). To understand the current performance of city bus systems and to compare it with the operations of the shared services offered by the paratransit system, the literature review focused on analytical methods to benchmark public transport systems. Benchmarking involves comparison of individual service enterprise efficiencies to the most efficient service of the sample under consideration. It is commonly carried out through frontier techniques which put the most efficient services on the frontier and evaluate the rest of the services relatively (Kotsemir, 2013).

2.2.1 Methods for performance efficiency benchmarking

Daraio et al. (2016) provide a comprehensive overview of the various methods and indicators used to compare public transport performance. They combine the varying methods adopted by transport planners and economists to develop a comprehensive set of indicators to measure the performance of bus systems and the analytical methods needed to develop these indicators. Broadly, performance benchmarking of public transport is carried out to measure the efficiency and efficacy of the system. Each operator is considered as a Decision Making Unit (DMU) to measure various input and output variables concerning the provision of public transport service. Input variables typically include physical and financial measures like hours of operation, number of depots, number of vehicles and employees, capital and operational expenditure on the system. Output variables typically include variables measuring the service supply and its usage i.e. capacity offered by the system, duration of service and the financial performance of the system i.e. the revenue generated. DEA is the most widely used method to combine these input and output variables into a scalar measure of operational efficiency.

The methods used for benchmarking analysis can be classified into parametric and non-parametric techniques. Stochastic Frontier Analysis (SFA) is the most preferred technique for parametric benchmarking while for non-parametric benchmarking, Data Envelopment Analysis (DEA) is the preferred technique (Aigner et al., 1977) (Meeusen and van Den Broeck, 1977). A comparative review of the results of alternative methods used for efficiency analysis of public transport systems was provided by (Jarboui et al., 2012, Brons et al., 2005, Sampaio et al., 2008). Their reviews conclude that there exists no significant difference between DEA and SFA in estimating the relative efficiencies of transit systems. However, SFA doesn’t consider more than one output variable and also includes external variables within the frontier analysis and hence doesn't establish their relationship with efficiencies explicitly (Garcia Sanchez, 2009). While DEA doesn't propose any mechanism to attain efficiency, it quantifies the changes needed for the inefficient unit to become efficient according to the outputs being sought (Saxena and Saxena, 2010). DEA also determines the weightages of each input and output variable within the overall efficiency as an output, as against the pre-determined weightages adopted by SFA (Sherman and Zhu, 2006).

2.2.2 Applications for performance efficiency benchmarking

Performance benchmarking methods explained above were applied for urban public transport systems in multiple contexts and at various scales. (Trompet and Graham (2012), Trompet et al., 2009, Sampaio et al., 2008, Trompet et al., 2018) have compared the performance of public transport systems across fifteen cities which are part of the International Bus Benchmarking Group (IBBG). These articles focus on identifying the normalised Key Performance Indicators (KPI) for effective performance comparison between cities with varying types of public transport capacities. The articles recommend indexing network efficiency performance of the system by operating cost, passenger-km and vehicle hours of service provided. Sampaio, Neto, and Sampaio 2008 adopted a DEA based approach for efficiency measurement of nineteen metropolitan transport systems in Brazil and Europe to understand the impact of institutional structure on system performance. The article concluded that systems with greater diversity in governance and one's with more tariff slabs have higher performance efficiency.

(Silver, 2013, Chang and Kao, 1992, Min, 2013) measured relative performance of five public and private bus operations in Taipei city. Their DEA based analysis showed an improvement in efficiency post liberalisation of the bus services in the city. The study by Nolan et al. (2001) carries out a data envelopment analysis (DEA) based analysis to measure the comparative operational efficiency of 25 selected mass transit systems in the U.S. The study found that higher than-average fleet age and federal subsidies adversely affected transit efficiency, whereas locally based subsidies had a positive impact. Min et al. (2015) compared the performance of twenty four mass transport operators within the city of Ohio, USA to identify sources of inefficiency across operators. The DEA based analysis identified lower performing operators with the objective of ensuring effective utilisation of mass transport subsidies.

2.2.3 Benchmarking of Indian bus systems

Applications of DEA to measure performance efficiency of Indian bus systems have been limited. Agarwal et al. (2010) used DEA to compare the performance of 35 State Transport Undertakings (STUs) providing intra-city and inter-city services for the year 2004-05 using both CCR and BCC methods. The scale efficiency of each of the STUs and the percentage reduction potential for various input resources to reach the efficiency frontier were derived. Accidents per lakh km of operation, fleet and staff strength were identified as the variables with significant efficiency improvement potential. Similarly, Saxena and Saxena (2010) applied CCR and BCC methods of DEA to study the performance of 25 Indian STUs between 2002-03 and 2004-05. Using fleet size, total staff and fuel consumption as inputs and passenger-km and seat-km of service as outputs, the article derives the relative efficiencies of STUs. The analysis identified the best and least performing STUs and their potential for improving their technical and scale efficiencies. However, both these articles combine intra-city and inter-city bus systems for their analysis, which wasn't an accurate comparison considering their varying operational characteristics, passenger requirements etc. Further neither of these studies evaluate the impact of external variables on the STUs' efficiency. Hence the findings from these studies don't provide conclusive insights on the specific measures needed to improve city bus systems. Gadepalli and Rayaprolu (2019) present a

DEA based approach to analyse factors affecting performance of urban transport systems in India. Eight urban bus services were analysed using three DEA models with separate output variables i.e. effective km for supply efficiency, passenger km for service consumption efficiency and total revenue for cost efficiency. Buses held, total staff and total cost were used as the common input variables across models. Additionally, external variables with significant correlation with bus system efficiency were established. Supply efficiencies remained relatively constant, but consumption and revenue efficiency varied over the years analysed. Among external variables, city population exhibited significant, but negative correlation with supply efficiency i.e. cities with more population have lesser vehicle-km per day. Consumption efficiency has a significant positive correlation with buses per million population and the share of trips between 5-10 km while revenue efficiency while revenue efficiency had a significant correlation with the overall economic performance of the city.

The summary of literature on applications of performance benchmarking explained above is presented in Table 4.

Table 4 Summary of literature on public transport performance efficiency benchmarking

Authors	Objectives	Data	Key findings	Method
(Chang and Kao, 1992)	Measure relative performance of public and private bus operations	Five intra-city bus operators in Taipei city	Improved efficiency after liberalising public transport services	DEA
(Nolan et al., 2001)	Impact of subsidies on efficiency of transit agencies	25 mass transit agencies in USA between 1989-1993	• Structure of government subsidy to transit agencies negatively affects both cost efficiency and technical efficiency • Federal operating subsidies create significant and negative impacts on technical efficiency, but local based subsidies are positively correlated with efficiency	DEA
(Sampaio et al., 2008)	Impact of institutional structure and tariff structure on Efficiency	19 public transport systems: 7 Brazilian cities data from 2001 and 12 European cities from 2005	• Higher no of participants in governance of system leads to better system efficiency Efficient systems have greater tariff options/ slabs	DEA
(Trompet et al., 2009)	provides a framework for benchmarking practitioners and policymakers that suggests the key variables to be considered for comparison between peers	13 cities of the International Bus Benchmarking Group (IBBG) between 2001-2007	• Variability exists between cities. • Depending on performance of each city on various indicators, area of improvement can be determined	Normalised KPIs
(Agarwal et al., 2010)	Compare performance efficiency of Indian bus agencies	35 Indian inter-city bus operators	Accidents per lakh km of operation, fleet and staff strength identified as the variables with significant efficiency improvement potential	DEA
(Saxena and Saxena, 2010)	Measuring performance efficiency in Indian State Transport Undertakings (STUs)	25 Indian STUs between 2002-03 and 2004-05	Passenger-km of demand identified as the key variable to understand efficiency of Indian STUs. Only a small fraction of Indian bus agencies are efficient, with significant scope for improvement among the rest	DEA

(Trompet and Graham, 2012)	Provides a framework for benchmarking practitioners and policymakers that suggests the key variables to be considered for comparison between peers	2010 data from the thirteen urban bus organizations in the International Bus Benchmarking Group (IBBG)	• Key Performance Indicators (KPIs) need to be normalised to compare them across cities. • Often, one KPI only answers part of a question. Need multiple variables to compare and rank organisations	Normalised KPIs
(Min, 2013)	Comparative efficiency of mass-transit systems in Ohio to ensure effective utilisation of Government subsidies	24 mass transport agencies in Ohio	• Urban mass transit agencies in high-density areas perform better compared to those in the suburbs. • Efficient public transport systems are correlated with better economic performance of city. • Efficient transit agencies are recommended to support management of inefficient systems to help improve their performance	DEA
(Trompet et al., 2018)	Performance data normalization to understand relative quality of bus transit agencies	IBBG 13 cities data between 2001-2015	• Performance variables need to be normalised for effective comparision between peers. • The following five characteristics are suggested for normalisation: o Average trip length o Proportion of revenue vehicle-km/ hours out of total vehicle-km/ hours o Average planning capacity of buses o Average commercial speed o Average vehicle weight	Normalised KPIs

	Factors impacting ridership loss in Indian city bus services using DEA for performance efficiency measurement and regression with external variables	7 Indian city bus services between 2009-10 and 2015-16	• Internal efficiencies remain relatively similar over the years • The efficiency values of systems showed significant correlation with external variables. o Supply efficiency negatively correlated with geographic spread of city. o Consumption efficiency positively correlated with trips between 5-10 km length o Revenue efficiency positively correlated with buses per million population and the economy of the city	DEA +Linear regression

2.2.4 Summary of transit performance efficiency literature

Formal public transport operators measure their performances using similar set of indicators, thereby making it feasible to compare their efficiencies with each other. Performance comparisons presented above were carried out between formal public transport systems i.e. total public transport service in cities, different bus operators within a city, comparison between bus operators of different cities. DEA based performance efficiency analysis has been demonstrated as a successful tool for transit performance efficiency globally. The key input and output indicators to measure performance efficiency are also identified.

However, none of the performance efficiency benchmarking articles compared efficiencies of formal and informal transit systems. The current thesis advances available literature by extending the performance benchmarking literature to compare public transport and paratransit system efficiencies. Developing a DEA based analysis to compare these service will require the input and output variables to be chosen carefully as the operational and institutional characteristics of paratransit mean that paratransit operators don’t maintain input and output indicator data similar to that maintained by formal systems. Hence, input and output variables concerning their physical measures of operations are identified to be better suited for such analysis. Passenger capacity of each vehicle and daily mileage are two such input variables which together define the service offered by both public transport and paratransit. Similarly, ridership and revenue are identified as two output variables that can be used across formal transit and paratransit systems. These variables were identified to be best suited for performance efficiency comparison between city bus and paratransit services in the Indian context.

2.3 Integrating paratransit into formal transit service planning

2.3.1 Public transport planning process

The transit-operation planning process is commonly divided into the following set of sub problems that can be solved sequentially at various stages of the planning process (strategic, tactical, and operational), and even during operations (real-time control) (Desaulniers and Hickman (2007), Gao et al., 2004, Guihaire and Hao, 2008, Ceder, 2016a):

i) Strategic planning problems that concern long-term decisions such as the design of the transit routes and networks such that the service is maximised for the city

ii) Tactical planning problems concern short to medium term decisions related to the services offered to the public like the frequency of service along the routes and the timetables. The solution to the route network design problem includes base frequencies of various route. Solutions to the tactical planning problems use these frequencies are adjusted to hourly variations in demand at the frequency setting stage

iii) Operational planning problems relate to short to medium term decisions on how the operations should be conducted to offer the proposed service at a minimum cost. They include a wide variety of problems such as vehicle scheduling, driver scheduling, bus parking and dispatching in garages, and maintenance scheduling

Each of these planning problems have been solved individually through various methods. Recent solutions to these problems combine a few of these stages to solve them iteratively. Figure 3 illustrates the traditional planning approach.

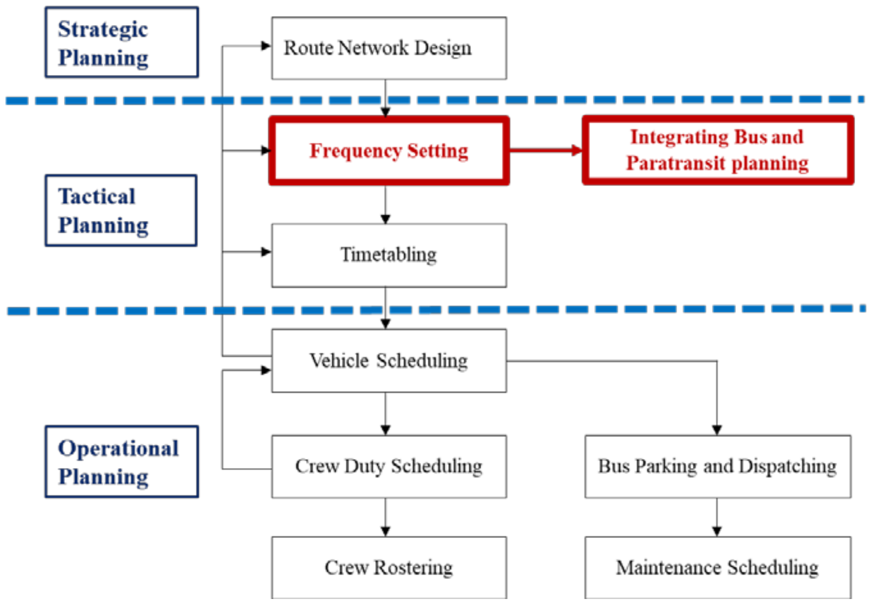


Figure 3 Stages of Transit planning and venue for intermodal integration

The operational planning procedure explained above is applicable for formal systems like bus and rail based public transport, where the entire planning and operations of the systems have traditionally been managed either by one or a few fleet operators working under a single organisation that plans for their services. Such systems follow a common planning and operations protocol, making it possible to integrate them at the strategic planning level i.e. during network design and frequency setting.

There currently exists no integration between public transport and paratransit modes. In fact, the public and paratransit systems compete with each other for ridership, rather than complimenting each other's services. An alternative approach where these services are integrated with each other can lead to the city rationalizing their services on various corridors, thereby maximising their overall availability to the citizens. Intermodal integration involves combining the operations of two systems which are optimized within their own system. They'll need to be planned together so that the service is optimized for the city's transport system (Ceder et al., 2013).

2.3.2 Current approaches for formal public transport and paratransit integration

This thesis intends to propose a methodology for integrating public transport and paratransit systems. Integration would involve the formal public transport mode to incorporate the presence of paratransit system and alter its service planning accordingly. The varying types of services provided by paratransit and their roles within the overall transport system in various developing countries across the globe were summarised by (Cervero, 2000) and (Cervero and Golub, 2007). Across countries, being privately managed and informal in nature has traditionally excluded them from the formal transit policy and planning processes. Many countries have unsuccessfully tried to eliminate these services from cities forcefully through regulation. Given the limited success in this approach, the need to integrate these services with formal public transport is now acknowledged globally (Phun and Yai, 2016, Cervero and Golub, 2007).

A wide range of approaches have been tried towards integration of paratransit services. Many Latin American and African countries with strong Central Business Districts (CBDs) adopted a network planning approach that involved moving paratransit from being a direct service to a feeder system to formal transit modes (Ferro et al., 2012). In many cities, the existing minibus based paratransit services have been replaced by formal systems like Bus Rapid Transit (BRT) corridors along the trunk routes, while the paratransit is designated a feeder role (Ferro and Behrens, 2015). However, such a re-orientation of network resulted in inconvenience to both passengers and paratransit operators. While passengers faced increased number of transfers for the same origins and destinations, the reduced requirement of paratransit vehicles resulted in reduction in fare income and jobs for their operators (Del Mistro and Behrens, 2015). This resulted in a return of paratransit services even to the trunk routes designated for formal transit (Ferro and Behrens, 2015, Ferro and Behrens, 2013).

Paratransit services in Asian cities are typically provided by small vehicles with passenger capacity not exceeding six, that offer flexible services in routes and schedules that are demand responsive (Phun and Yai, 2016). Such services are either provided by individual operators along various high demand routes or a self-organised group of operators that provide services within a defined service zone. Even in the Asian cities, the development of mass transit systems has not resulted in reduction in paratransit services, due to the lack of physical and fare infrastructure between various services and the operators' dependence on paratransit as a source of livelihood. This is highlighted by studies like Basuki Joewono and Kubota (2008) and (Yaakub and Napiah, 2011) that analysed travel behaviour of paratransit users.

Altering institutional and governance practices to integrate paratransit services have also been attempted. The operators of Matatus, the paratransit service in Kenya have formed self-organised Savings and Credit Cooperatives (SACCOs) to improve their services. The SACCOs monitor and improve performance of their members through measures like operational and fare management, incentives to drivers like salaries and loans for improved access to finances and compliance with Government policies (Behrens et al., 2017, Thaimuta and Moronge, 2014). However, selective compliance of some operators to the organisation's objectives has led to violations in route adherence, crew qualifications and working hours of drivers. This further led to the matatu operations being unpredictable and chaotic, while also eroding the trust between the Government and SACCOs. The case of paratransit systems in Nigeria that face similar challenges were presented by Shittu (2014), where a quasi-formal management approach to address the challenges was proposed.

In summary the need to integrate paratransit services into the planning and governance practices, while acknowledging the socio-economic and mobility benefits offered by their operations is recognised by a majority of the literature on paratransit systems. However, a detailed understanding of the operational performance efficiency of both the modes and specific areas of improvement required for such integration have not been established previously.

2.3.3 Approaches for feeder service and Demand Responsive Transit (DRT) design

Majority of the literature on paratransit integration are the one's solving the problem of providing shuttle services as feeders to main haul public transport systems. Ceder (2016b) defines shuttle services as those that provide reliable and synchronised service for efficient transfer to the main-haul transit system. Ceder (2009) developed a multi-criteria decision making method for designing feeder services to ease the main-haul public transport usage. An optimisation algorithm to maximise passenger demand was developed to evaluate alternative route strategies for shuttle services i.e. fixed Vs feeder services and was solved using both integer programming and heuristic methods with similar results. The problem was formulated for a test network and was later applied for Castro Valley's blue line of BART (Bay Area Rapid Transit), California, USA. The article recommends designing shuttles as Demand Responsive Transit (DRT) services which alter as a function of demand.

Ceder (2013) extended the routing strategies proposed by Ceder (2009) by proposing a methodology to examine alternative operational strategies and routing scenarios from both user and operator's perspectives. A simulation model was developed to evaluate alternative routing strategies. Analysis for a test network and the real-world case of Castro Valley in California compared results between fixed route and flexible schedule shuttle services. Fixed route strategies combined with operational strategies like short turns and bidirectional services were observed to have similar performance as DRT services. The article establishes the need to use Intelligent Transport System (ITS) to consider operational strategies during shuttle service design thereby improving its efficiency.

Kim et al. (2009) proposed a methodology which can be used for both normal transit and shuttle service design. Their model was applied to optimise frequency and subsequently generate timetables for a demand and time responsive model that uses stop level microdata. The frequency optimisation was carried out with an objective function minimising the total of user and operator's costs with constraints on subsidy, fleet size and minimum policy headway, using the real-world case of Seoul. Kim and Schonfeld (2014) present an approach to integrate conventional and flexible bus services through times transfers through probabilistic optimisation models incorporating stochasticity in travel and wait times. The fleet sizes were optimised to minimise user and operator cost due to coordination in passenger transfers, common headways and their slack times. The solution was demonstrated for test networks and was solved using Genetic Algorithm. Dikas and Minis (2014) focus on ways to provide demand responsive services for another 'paratransit' category of users i.e. people with mobility challenges. The current Standard Paratransit Transport System (SPTS) assumes predefines bus stops and their prescribed sequence. This study developed a Genetic algorithm based optimisation wherein paratransit routes are altered based on level of disruption of the nominal routes, seat availability and ratio of time window for transfers to scheduled headway. While the approach for integration presented in the article is relevant, it is still focussed on integrating the routes and frequencies of demand responsive systems with formal transit agencies.

2.3.4 Summary of previous approaches towards paratransit integration with formal transit

Majority of the articles on paratransit integration, feeder service design and Demand Responsive Transit (DRT) systems adopted an integrated route network design approach for these services to act as a feeder to the main haul public transport system. However, such a network design approach can't be applied for the case of bus and paratransit systems due to the following reasons:

i) Paratransit operates as an independent service by themselves and aren't necessarily a feeder system to the formal public transport system.

ii) Even though they don't operate under a single fleet operator, the independently operated paratransit services also follow the same route network pattern

iii) The solution of the transit network design problem allocates base frequencies for all the routes. Given the dynamic nature of paratransit operations, developing long-range route plans will negate their current demand responsive nature by being able to switch between routes.

iv) In a city which has an existing public and paratransit system, it is highly likely that the strategic planning components i.e. the corridors of operation of the transit systems would have evolved over the years according to the travel demand patterns of their users (Mani et al., 2012a, Gadepalli, 2016)

Therefore, the paratransit route network offers limited flexibility for change. Findings from (Del Mistro and Behrens, 2015) show that a trunk and feeder style planning of existing paratransit and formal public transport has seen limited success. In fact, even in case of formal public transport systems, literature shows that it is encouraged not to change the route network frequently to ensure continuity of routes that people have been familiar with (Gallo et al., 2011, Verbas et al., 2015a).

Therefore, it is identified to be more appropriate to intervene at the tactical planning level of public transport planning i.e. frequency setting. Tactical planning is a short to medium term exercise which can be reviewed periodically every three months or one year. Such an approach will allow for paratransit to be designed as a parallel service to formal public transport. The periodicity in updation will also help in retaining the flexible nature of paratransit services.

2.4 Solution methods for Transit Network Frequency Setting Problem (TNFSP)

The remaining part of the literature review describes the methods used for solving the Transit Network Frequency Setting Problem (TNFSP) and their applicability for the current problem. TNFSP involves identifying the optimum frequency of each route of the public transport network such that the user requirements like minimising waiting time, total travel time, crowding etc. are balanced with the operator’s constraints like cost of operations, availability of fleet etc. Solutions for the TNFSP can broadly be classified into two categories:

i) Single-level solutions where transit demand and frequency needs are modelled together

ii) Bi-level solutions where transit demand assignment and frequency optimisation are carried out separately.

The literature review for each of these solution methods is explained in this section.

2.4.1 Single-level solutions for transit demand and frequency optimisation

Initial solutions for the TNFSP developed by (Mohring, 1972, Newell, 1979) proposed the square-root rule i.e. route frequency to be proportional to the square root of the ratio of waiting cost to passengers and the operational cost of the transit system. Many subsequent solutions considered user and operator costs separately. Solutions by (Jansson, 1980, Schéele, 1980, Han and Wilson, 1982, Constantin and Florian, 1995, Grosfeld-Nir and Bookbinder, 1995) adopted minimising users' cost as the key objective while deriving route frequencies. The variables to measure user cost varied across studies.

Schéele 1980 developed a non-convex frequency optimisation model for bus routes in the city of Linkoping in Sweden. The Origin-Destination (OD) matrix for buses was assigned to the network using capacity constrained method to derive link-wise trave demand for which, heuristics techniques were used to derive the optimal frquencies to minimse users total travel time across the system. (Han and Wilson, 1982) developed an optimisation framework for bus fleet allocation for networks with multiple overlapping routes. Passenger assignment was carried out based on minimizing transfers and in-vehicle travel time while bus allocation to routes was based on maximum crowding criteria i.e. buses are allocated until load factor is acceptable, with constraints on maximum fleet availability. The methodology was later demonstrated for the case of Cairo.

Constantin and Florian (1995) formulated the frequency design problem as a bi-level non-convex optimization model, and solved the model by a projected gradient algorithm. The frequency was determined to minimize the total cost of travel for the passengers. Optimal strategy assignment model with fixed demand was used to determine passengers' route choice behaviour. Martínez et al. (2014) developed a more advanced solution to use a Mixed Integer Linear Program (MILP) formulation for the frequency optimisation model proposed by (Constantin and Florian, 1995). This was solved using an exact solution for smaller networks and using a meta-heuristic solution for large scale networks. Grosfeld-Nir and Bookbinder (1995) develop a methodology for frequency optimisation based on Crowding Over a Distance (COD) as opposed to minimising crowing on the peak load section and Probability of Failure (PoF) i.e. periodicity of people unable to catch the bus due to overcrowding. In summary, waiting time, total travel time and bus crowding were the most used decision variables for user cost while constraints typically included fleet availability, passenger costs and user subsidy to be provided. Most of these studies used non-linear modelling methods and derived approximate solutions for fictitious or small-scale test networks.

While the above solutions approached the problem from the users' perspective, Ceder (1984) proposed an alternative method which analyses the problem from the operators' perspective by solving it to minimise the number of bus runs and fleet required while meeting the demand. Hadas and Shnaiderman (2012) also adopted the maximum load section method while adding an additional objective of minimising the empty seats. This study uses modern methods like Automatic Vehicle Location (AVL) and passenger count data to derive the optimal frequencies for various routes. Jara-Díaz et al. (2008) take the maximum load section approach forward by comparing frequency requirements for aggregate demand at the route level and disaggregate demands in terms of Origin-Destination (OD) pairs. The study identified that aggregated analysis of demand results in underestimation of frequency and over-estimation of vehicle size. It recommends smaller capacity and high frequency services for the case of Santiago, Chile to maximise wait time savings for users. Gallo et al. (2011) solved for frequency optimisation under elastic demand conditions that consider the impact of transit supply in the public transport modal share in multimodal networks. A multimodal assignment covering car and transit users was used to determine network loads under elastic demand conditions. Further a heuristics based solution approach was adopted to derive optimal frequencies. The solution approach was demonstrated for the case city of Salerno, Italy.

Deriving frequency by considering both user and operators' objectives have also been attempted. Furth and Wilson (1981) proposed a formulation which maximizes societal benefits which combines both users' objective of waiting time savings and the operators' objective of ridership maximization on the transit system. This formulation was later extended by Verbas and

Mahmassani (2013) to optimise pattern headways i.e. a subset of the total stops within the route maximising riders' wait time savings and minimising the cost of operations was developed. This solution was used by Verbas et al. (2015a) to estimate the demand elasticities on the Chicago transit network for temporal, spatial and spatio-temporal variations.

The summary of the single-level frequency optimisation models explained above is presented in Table 5.

Table 5 Summary of single-level transit assignment and frequency optimisation

Article	Objective function	Approach	Solution method	Case
(Mohring, 1972), (Newell, 1979, Jansson, 1980)	Minimise total user and operator costs	square-root rule i.e. route frequency to be proportional to the square root of the ratio of waiting cost to passengers and the operational cost of the transit system	Mathematical optimisation	Test network
(Schéele, 1980)	Minimise user travel time in the system	Compound minimisation problem considering capacity constraints and demand elasticity to frequency	Non-linear programming	Linkoping
(Furth and Wilson, 1981)	Maximise wait time savings and ridership	Frequency designed as a constrained resource allocation problem with constraints on subsidy, fleet size, and maximum headways	Mathematical optimisation	Boston
(Han and Wilson, 1982)	Minimise passenger wait time and crowding levels subject to network capacity constraints	Solves of frequency planning in systems with overlapping routes by decomposing pronlem into base allocation and surplus frequency allocation	Mathematical optimisation	Cairo
(Grosfeld-Nir and Bookbinder, 1995)	Minimise buses required to meet service crietria	Crowding Over Distance (COD) and Probablity Of Failure (POF) considered as service constraints instead of traditional metrics like maximum load section		DAN, Israel
(Jara-Díaz et al., 2008)	Minimise user cost (total travel time)+operator cost (fixed and variable)	Aggregate level demand for route and disaggregated Origin-Destination (OD) pairs between stops	Analytical	Santiago, Chile
(Gallo et al., 2011)	Minimise user costs	Multimodal assignment with elastic demand considering impact of transit supply on car and transit users	Heuristic method	Salerno, Italy
(Hadas and Shnaiderman, 2012)	Minimise cost of operation including i) empty seats driven, ii) overload and unserved demand	AVL and passenger count data as demand input	Sensitivity analysis	Test network

(Codina et al., 2012)	Cost of operations plus cost of total time spent by users in the system	Stochastic user equilibrium	Non-linear Mixed Integer Program using CPLEX	Test network
(Verbas and Mahmassani, 2013)	Two objectives are considered i) Maximise ridership and wait time savings ii) Minimise net cost of operation with constraints on budget, fleet and policy headway	Based on pattern headways at half-hour intervals	Mathematical optimisation using APML/KNITRO platform	Test network
(Martínez et al., 2014)	Minimise total travel time for users	Links assumed to have sufficient capacity for any transit load	Metaheuristic Tabu search solution	Rivera, Uruguay
(Verbas et al., 2015b)	Impact of frequency optimisation on stop level demand elasticities	Frequency optimisation solved for pattern headways at half-hour intervals,	Mathematical optimisation and sensitivity analysis	Chicago

2.4.2 Bi-level solutions with separate assignment and frequency optimisation models

Many of the above mentioned solutions consider Origin-Destination (OD) demand patterns in the city and the network flows to be constant. However, in real world conditions, the OD and traffic flow patterns change in response to the changes in supply. This variable nature of passenger demand on the transit network is captured by bi-level solution methods. These methods carry out user assignment on to the transit network and the operators' frequency planning problems separately and solve the overall problem iteratively. The lower level of the solution typically contains transit assignment to the network while the upper level optimises frequencies to meet these demands. Compared with single-level programming, the bi-level programming has incomparable superiority, in the following ways:

i) It can simultaneously analyse two independent and conflicting objectives;

ii) The multi-value decision method of bi-level programming is more practical;

iii) It can explicitly indicate the interaction between the supply side and the demand side

Hence majority of recent literature on frequency optimisation uses this bi-level approach. Gao et al. (2004) presented a bi-level approach with a deterministic user equilibrium based transit assignment in the lower-level and a frequency optimisation model in the upper level. The frequency optimisation was solved with the objective of minimising the total passenger cost and fleet operations cost subject to constraints like minimum frequency to be maintained on each route and the maximum fleet available. A heuristic solution was developed for a test network and its sensitivity analysis was presented using sample data. Zhou et al. (2005) used a game-theory based approach to model frequency optimisation between competing operators. The lower-level solution was modelled as a stochastic user equilibrium model with elastic demand while the frequency was optimised in the upper level where-in operators were considered as non-cooperative players in a

Nash game. A stackelberg form heuristic solution was developed for a test network which demonstrated that transit operators can achieve competitive advantages by improving their service quality, thereby being more beneficial to passengers. The operators with service on the same path can cooperate to compete with those on alternative paths so as to attract more passengers and hence greater revenue.

The bi-level frequency optimisation approach by Yu et al. (2007) adopted optimal strategies based transit assignment in the lower level to model route choices of passengers. Optimal strategies assignment, developed by Spiess and Florian (1989), models route choice in an uncongested transit environment. Hence, the impact of congestion is modelled in the upper level of the model where congestion is assumed to be induced by the frequency of the service. The frequency optimisation was solved using Shuffled Complex Evolution (SCE) method of heuristics to minimise total cost of operations and users total travel time, with fleet size constraints to reflect congestion. The solution was tested for the case of Dalian bus company in China where travel demand patterns were estimated through on-board surveys. Yu et al. (2010) extended this methodology by developing a genetic algorithm based solution for the same model framework and data-sets. Yoo et al. (2010) adopted a capacity-constrained stochastic user equilibrium assignment with variable demand, considering transfer delays between transit lines in the lower level. The frequency optimisation in the upper level was solved using a non-linear optimisation model using gradient projection method to maximise network demand while considering fleet-size and frequency constraints. An application of the proposed model and algorithm is presented using a small test network.

Dell'Olio et al. (2012) developed a combined bus-size and frequency optimisation solution using the bi-level modelling approach. The lower-level model assigned public transport trips using the user equilibrium model with constraints on vehicle capacity that balances vehicle size and frequency. A mathematical optimisation approach was adopted for frequency optimisation with the objective of minimising societal cost i.e. the combination of users travel cost and operators fixed and operational costs. User costs covered costs of in-vehicle time, wait-time, access time and transfer delays of public transport users. Operators' costs included operational cost per km, hourly cost of standing still with engine running, personnel costs and fixed costs. The optimisation was carried out using Hooke-Zeeves algorithm solution has been applied for the case of Santander city in Spain.

Codina et al. (2012) and Huang et al. (2013) developed frequency optimisation solutions that consider the variability in the network. Codina et al. (2012) modelled frequency requirements for occasional high demand situations like celebration of massive events. The model considers delays experienced by buses as a consequence of the get in/out of the passengers, queueing at stations and the delays that passengers experience waiting at the stations. The method of successive averages was applied for the case of a congested strategy based user equilibrium passenger assignment with strict capacities on the bus lines. The frequency optimisation was carried to minimise the total travel time and operational costs. Huang et al. (2013) proposed a bi-level model to optimise bus frequencies in case of uncertain passenger demand. The objective function includes i) transit network cost consisting of passengers' expected travel time and operating costs and ii) the transit network robustness performance, indicated by the variance in travel time. An optimal strategies based transit assignment was carried out in the lower-level of the model taking Liupanshui city in China as a case and was solved using genetic algorithm.

Hadas and Shnaiderman (2012) present a bi-level frequency optimisation model that uses advanced sources of information like Automatic Vehicle Location (AVL) and Automated Fare

Collection (AFC) systems which provide accurate data of fluctuations in service supply and demand. The transit assignment was carried out for both deterministic and stochastic demand scenarios. The optimisation minimises total cost of operation including operators cost measured as empty seat-km driven and users cost measured as overloaded and un-served demand. The study also carried out sensitivity analysis of the costs from the operator and city authority points of view. From the operators' point of view, it is desirable to utilise available fleet efficiently while from the authority point of view, providing adequate level of frequency is the key concern.

Verbas and Mahmassani (2015) adopted a service pattern approach to solve the bi-level TNFSP problem. The approach derives headways within 30 min intervals for each service pattern i.e. a subset of stops within a route. Such an approach helps in designing the system for high demand segments or corridors within the overall route network, instead of designing the entire route frequency for the single maximum demand segment. The transit assignment in the lower level is carried out using the multi-modal time-dependent user equilibrium for travel time hyperpaths. The optimisation algorithm for frequency setting in the upper level maximises wait time savings for users subject to fleet, vehicle loading, budget and policy headway constraints. The optimal frequencies were derived through two methods: a stand-alone method that solves the two levels sequentially and an integrated method that solves both levels iteratively until the additional waiting time savings become negligible. The results from the stand alone and integrated solution methods were comparable, leading further to the conclusion that a stand-alone solution is useful for short to medium term decisions while an integrated solution can be used for medium to long-term strategic decisions. Summary of the bi-level TNFSP solutions explained above are summarised in Table 6.

Table 6 Summary of literature on bi-level transit assignment and frequency optimisation

Authors	**Solution Method**	**Upper level frequency optimisation model**	**Lower level transit assignment model**	**Data**
(Constantin and Florian, 1995)	Non-linear mathematical optimisation	Minimising users' cost subject to constraints on waiting time, total travel time and bus crowding	Optimal strategies	Stockholm, Winnipeg and Portland
(Gao et al., 2004)	Heuristic solution	Minimise passenger travel time and fleet operation costs while meeting minimum frequency constraints	Deterministic user equilibrium assignment	Test network
(Zhou et al., 2005)	Heuristic solution (using a Stackelberg form problem)	Maximise profit of operator by changing fares. Operators considered as non-co-operative players in a Nash game	Stochastic user equilibrium with elastic OD matrix	Test network
(Yu et al., 2007)	Heuristics (Shuffled Complex Evolution (SCE) method)	Minimise total cost of operators and users wait time + in-vehicle time	Optimal strategies	Dalian Bus Company, China
(Yu et al., 2010)	Genetic Algorithm	Minimise total travel time of passengers Subject to fleet size constraint	Optimal strategies	Dalian Bus Company, China
(Yoo et al., 2010)	Non-linear optimization model using gradient projection method	Maximize demand while considering fleet size and frequency constraints	Capacity-constrained stochastic user equilibrium assignment variable demand, considering transfer delays between transit lines	Test network
(Dell'Olio et al., 2012)	Mathematical optimisation using Hooke-Zeeves algorithm solved by iterative balancing method	Minimise social cost i.e. total of user and operator costs: i) Users total cost includes fare, in-vehicle travel time, wait, access and transfer times ii) Operators' costs includes operational cost per km, hourly cost of standing still	PT equilibrium assignment using ESTRAUS public transport and traffic simulator model, considering transfer delays between transit lines	Santander, Spain

		with engine running, personnel costs and fixed costs Subject to technological constraints and demand satisfaction		
(Huang et al., 2013)	Genetic algorithm	Minimise users travel time and operators cost including the following two terms: i) Transit network cost, consisting of the passengers' expected travel time and operating costs ii) Transit network robustness performance, indicated by the variance in passenger travel time	Optimal Strategies	Liupanshui city
(Verbas and Mahmassani, 2015)	Mathematical optimisation using AMPL/ KNITRO platform for stand-alone bi-level solution, Heuristics for integrated bi-level solution	Maximise wait time savings for users subject to fleet, vehicle loading, budget and policy headway constraints	Multi-modal time-dependent user equilibrium for travel time hyperpaths	Chicago city

2.4.3 Approaches for transit assignment

In addition to the frequency optimisation literature presented above, transit assignment has been handed separately as well and the key findings from the literature are summarised here. Friedrich and Wekech (2004) present alternative approaches to model transit assignment and algorithms to solve them. Line-based or frequency based assignments and schedule-based assignments. Frequency based assignments assumes uniform flow of vehicles and passengers thereby considering average headways, wait-times and transfer times for assignment. Schedule-based assignment considers the timetable of each transit line with its exact departure and arrival times. Frequency based assignments were observed to be more suited for urban settings with continuous transit supply while schedule based assignments are more suited for rural and inter-city settings with intermittent frequency distribution. A schedule based assignment was also observed to have longer computational time and it doesn't always find shortest paths for assignment. The article also identified branch and bound search as a better alternative to shortest path search of assignment.

Within these two models of transit assignment, various approaches of route choice allocation were presented in literature. Majority of the literature on frequency optimisation used optimal strategies technique for transit assignment, as presented in Spiess and Florian (1989). This method only identifies passenger's route choice in uncongested networks. Subsequent transit assignment used alternatives like capacity constraint, user equilibrium and stochastic-user equilibrium models for assignment. Further refinements of these approaches were presented in the literature to capture passengers' travel behaviour in a more granular detail.

Cepeda et al. (2006) presented a new frequency based transit assignment approach that models congested transit networks with capacity constraints. A Method of Successive Averages

(MSA) based heuristic algorithm was developed to derive equilibrium link flows and was demonstrated for the case of Stockholm city. Hamdouch and Lawphongpanich (2008) presents the application of MSA based transit assignment in capacity constrained networks using user equilibrium method.

2.4.4 Summary of literature on TNFSP

Initial solutions for TNFSP used single level models for transit assignment and frequency optimisation. Recent literature points to bi-level frequency optimisation as the preferred approach, with transit assignment solved in the lower level of the problem while frequency optimisation is carried out in the upper level. The stand-alone bi-level method presented by Verbas and Mahmassani (2015) which produced robust results for the short to medium term solutions is identified to be the best approach to solve for integrated TNFSP for bus and paratransit systems. Such an approach will account for the operators updating their frequencies in response to the varying travel demand patterns, which is an integral feature of paratransit systems.

The two key approaches for transit assignment are-schedule based assignment and frequency/ headway based assignment. Since paratransit doesn't adhere to a fixed schedule, a frequency or headway based assignment was identified to be more appropriate for the current thesis. The transit assignment problem was initially solved using optimal strategies method, which doesn't consider congestion of vehicles while assigning route choices of users. Given the known elasticity of demand due to congestion, more recent approaches have used variations of capacity constraint method for single mode assignments and user equilibrium method for multi-modal transit assignment. A headway based transit assignment using user equilibrium method was identified as the most suited option for the current case of multi-modal network with bus and paratransit services, as paratransit offers unscheduled but high frequency services.

The upper level frequency optimisation solutions of these models typically have objective functions maximising societal benefits by minimising cost of operators and travel time of users and maximising transit usage. Travel times are measured as a combination of wait times, travel times and transfer times. Some formulations adopted maximising societal benefits or minimising social costs using variables like waiting time savings, operator profit and transit ridership as their objective function. In the current urban mobility context, societal costs and benefits extend beyond transport variables and have to comprise of the overall congestion, Green House Gas (GHG) emissions and air-quality implications. Therefore, the societal impacts of alternative public transport scenarios are proposed to be analysed separately.

The solution methods for TNFSP typically adopt mathematical optimisation, heuristics or meta-heuristics. Majority of the mathematical optimisation solutions in literature were for test networks or for small networks, while many large-scale real-world applications were solved using heuristics or metaheuristic methods like Genetic Algorithm (GA), simulated annealing or Tabu search methods. Given the stand-alone nature of the bi-level problem adopted for this study and the availability of advanced commercial solvers for optimisation, we adopted a mathematical optimisation approach to solve for integrated bus and paratransit TNFSP.

2.5 Summary of literature review and gaps identified

The chapter presents a comprehensive literature review on planning of formal public transport and informal paratransit systems. The available literature on users' and operators' characteristics on paratransit services and their relative features compared to formal systems is limited. Majority of the literature on user characteristics focusses on choice behaviour of formal public transport users as compared to private vehicle users but not paratransit systems. Similarly, the operators' performance analysis literature focuses on efficiency analysis of formal public transport systems as a function of internal and external variables with limited focus on paratransit services. Majority of the available literature on paratransit systems focuses on the operators' livelihood issues and their Governance frameworks, with limited attention to their operations planning issues.

The limited literature available on formal public transport and paratransit systems primarily recommends a trunk and feeder style system where paratransit acts as the feeder to the formal public transport systems providing trunk services. However, implementation of such systems found limited success due the inconvenience it causes both to the users and operators. While users are inconvenienced since they have to make more transfers, paratransit operators don't operate for long in such systems as they will have to operate only on feeder routes which typically offer limited demand and revenue making potential. Therefore, it is important to integrate paratransit planning into the overall public transport planning framework and recognise it as an independent but complementary service rather than as a feeder service to formal public transport.

3 Methodology for integrated planning of bus and paratransit services

The aim of this thesis is to develop a transit planning and optimisation framework that integrates bus and paratransit services and apply it for the case of one Indian city. As explained in section 2.3.4, majority of the literature focusses on designing paratransit as a feeder to the formal bus services using a route network design approach. However, this approach witnessed limited success due to the inconvenience it caused for both users and operators i.e. users had to make more transfers in a trunk and feeder system while operators had to shift to low-demand routes (Ferro et al., 2012, Del Mistro and Behrens, 2015).

The current thesis recognises paratransit as a shared mode of transport, operating as an independent system with its own route network where operators switch between routes in a demand responsive manner. An integrated planning framework that ensures that the two modes complement each other is developed where the formal transit system provides fixed route fixed schedule services while paratransit provides high frequency services during peak hour, thereby reducing the additional peak-hour demand on the formal public transport systems. Such an arrangement would reduce the incremental bus service needs during the peak hour, allowing for a more balanced resource allocation of bus services throughout the day. Hence, we designed the bus and paratransit integration as a tactical planning problem and solved for an integrated frequency optimisation of buses and paratransit services to test its impacts. Solving the frequency setting problem requires modelling users' travel demand patterns, operational characteristics of existing services and optimizing their service frequency according to travel demand.

The methodology adopted to solve each of the stages are summarised in Figure 4. The detailed methodology adopted for each of the components and the novel elements of the thesis compared to the available literature are explained in the following sections according to the objectives set for the thesis. Section 3.1 explains the methodology for objective I i.e. comparative user characteristics analysis of bus and paratransit users, while section 3.2 covers objective II i.e. to compare their relative operational characteristics. Sections 3.3 covers the methodology adopted for integrated frequency optimisation and its impact on the society i.e. objectives III. Section 3.4 demonstrates the proposed solution through an illustrative network example. Section 3.5 explains the alternative demand and supply scenarios tested to inform decision making on the mix of public transport services in the city i.e. objective IV of the thesis.

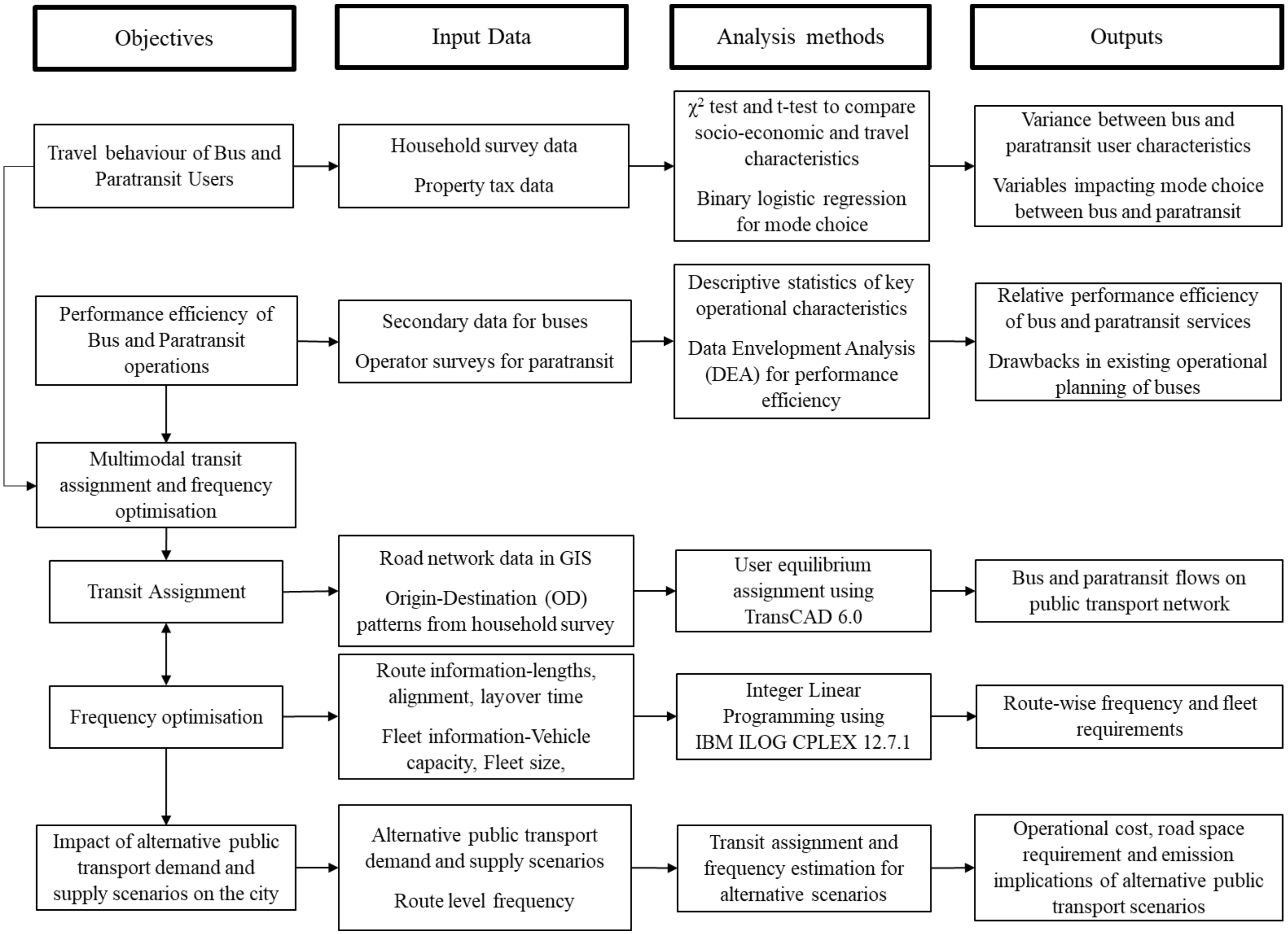
3.1 Establishing user's travel demand characteristics

A detailed analysis of bus and paratransit users will help understand which of their characteristics are similar and which of them vary thereby providing inputs to their relative mode choice preferences which can further be used to design the supply of the two systems to meet their demand optimally. Hence the current thesis analyses bus and paratransit user characteristics in detail. Establishing travel demand characteristics of formal transit and paratransit users requires a comprehensive analysis of their users socio-economic and travel characteristics. The literature review has shown that such an exercise has not been done previously in cities of emerging economies. The current thesis addresses this gap in literature by taking the case of Visakhapatnam, a medium sized Indian city. The data collection and analysis methods adopted for the study are explained in the following sections.

3.1.1 Data collection methodology

A household survey based data collection and analysis was adopted as the best methodology to establish the travel characteristics and mode choice behaviour of both formal and informal transit users (Stopher and Greaves, 2007). We present a city-wide household interview method to collect the activity and travel diary data of public transport and paratransit users across modes. A stratified sampling strategy was adopted to capture the heterogeneity in socio-economic and travel characteristics of users across various households in the city. The property tax database of the city was used as the input to identify the likely income category of the household i.e. households paying higher property tax stay in larger houses and were therefore assumed to be from a higher income level. The sample size for the surveys was determined for each municipal word based on probability sample tests presented in Biemer and Lyberg (2003).

Figure 4 Methodology overview for the thesis



The specific approach to determine the sample size in various wards of Visakhapatnam, the case city, is explained in section 4.2 of the thesis. The questionnaire used for the survey is summarised is Table 7. It captures general information pertaining to the entire household and the information specific to each individual in the household. The general information about the households included information regarding their income, number of members and vehicles owned, which was used to classify them into various socio-economic groups. Individual specific information of the questionnaire captured information related to each individual's age, gender, education, occupation and income along with their detailed travel behaviour. The detailed travel behaviour of individuals included their activity patterns and trip chain data from the day before the survey. Such a methodology was identified by Stopher and Greaves (2007) as the best chance of capturing users travel behaviour patterns at the city level.

Table 7 Questionnaire for household surveys

Type of data	**Variables collected**
Personal information	Age
	Gender
	Occupation
	Monthly income
	Vehicle ownership and age of vehicle
Trip making information	Trip purpose
	Trip origin
	Trip destination
	Travel distance
	Mode used
	Access mode
	Egress mode
	Name of public transport stop at origin
	Name of public transport stop at destination

	Distance to access public transport stop
	Distance of egress public transport stop
	Access travel time
	Egress travel time
	Average waiting time for public transport (or paratransit)
	Total travel time
	Total travel cost
	Reason for using the mode used

3.1.2 Household survey data analysis

The household data was analysed using the methodology presented by Khattak and De Palma (1997) and Le-Klähn et al. (2014) to establish the detailed profile of formal public transport i.e. city bus services and paratransit i.e. shared auto-rickshaw users. The user characteristics of both modes of shared transport were compared across each of the socio-economic and travel variables. Statistical tests were carried out to measure the variance between the bus and paratransit user groups for each of the variables. Within the socio-economic characteristics χ^2 test was used for categorical variables like gender, occupation, income range and vehicle ownership, while the t-test was used for age, which is a continuous variable. All the travel characteristics i.e. travel time, trip length etc. are continuous variables for which t-test was used to measure variance between bus and paratransit users. Further, a logistic-regression analysis with mode choice as the dependant variable and user characteristics as independent variables was carried out to identify the key variables impacting user choice between public transport and paratransit systems.

Such detailed profiling of users of both the modes and their choice behaviour between the modes will help policy makers and planners in understanding the city's public transport user behaviour in an integrated manner. This will in turn support them in planning the services to serve the user needs better, thereby maximising transit ridership.

3.2 Operator characteristics and efficiency comparision between bus and paratransit services

Available literature on the comparative operational characteristics and performance efficiency of public and paratransit agencies is limited. However, performance efficiency of formal public transport systems has been carried out previously. Performance efficiency measurement of public transport systems is typically carried out through a combination of multiple input and output variables. Input variables typically include physical and financial resources required to operate the system including hours of operation, number of depots, number of vehicles and employees, capital and operational expenditure on the system. Output variables typically include variables measuring the service supply and its usage i.e. capacity offered by the system, duration of service and the financial performance of the system i.e. the revenue generated (Daraio et al., 2016, Jarboui et al., 2012). These variables are combined through non-parametric methods like Data Envelopment Analysis (DEA) and Stochastic Frontier Analysis (SFA) to generate a ratio of outputs to inputs of each transit system or operator for comparative efficiency measurement. The current thesis extends the DEA analysis, previously applied for formal transit systems, to compare the efficiency of city bus and paratransit systems. Many of the input and output indicators available for formal transit systems are not available for paratransit services, given the lack of a single agency monitoring the operational performance of all paratransit operators. Therefore, primary surveys to collect the operational performance data of paratransit systems has been conducted in the case city. Key input variables like daily mileage, vehicle capacity and output variables like revenue and ridership were collected through the survey. Similar data for the bus system was available thought secondary sources. Further, the input-output analysis for the formal public transport systems is carried out in a greater detail through regression analysis.

3.2.1 Comparision of efficiency of bus and paratransit systems

The operational efficiency of the two systems was analysed using Data Envelopment Analysis (DEA), a non-parametric mathematical programming technique to measure the productivity of a firm or entity. Each firm or entity is defined as a Decision Making Unit (DMU). DEA quantifies the relative efficiency of DMUs as a ratio of the combination of its outputs and inputs (Equations 1-4) (Coelli, 1996, Saxena and Saxena, 2010, Sampaio et al., 2008, Daraio et al., 2016). DEA defines the most efficient DMU to have an efficiency score of 1 and measures the relative efficiency of the remaining DMUs in reference that. Therefore, it is formulated as an optimisation problem where individual DMUs are maximising their efficiency to reach the most efficient DMU.

Equation 1 provides the objective function to maximize efficiency h of target DMU j_0. The ratio of outputs to inputs was used as a measure of efficiency where a total of n DMUs operate with m inputs and s outputs; y_{rj} is the amount of r^{th} output from entity j, and x_{ij} is the amount of i^{th} input from the same entity j. The decision variables $u = (u_1, u_2, \ldots, u_r, \ldots, u_s)$ and $v = (v_1, v_2, \ldots, v_r, \ldots, v_m)$ are weights given to the s outputs and m inputs respectively. These variables are derived through the iterative optimisation exercise. Thus, the objective equation is iterated n times to calculate the relative efficiencies of one entity at a time. The constraints provide the upper bounds of efficiency of individual entities and lower bounds of weights assigned to inputs and outputs. Equation 2 constrains the efficiency of any entity i.e. its ratio of outputs to inputs isn’t greater than one. In other words, the most efficient entity has an efficiency of 1 and the rest are measured relative that, going down to a minimum of zero. Therefore, it is formulated as an optimisation problem where individual DMUs are looking to maximise their efficiency to reach the most efficient DMU. The constraints provide upper bound for efficiency i.e. 1 and lower bound for the weights i.e. 0 to ensure non-negative efficiencies for all DMUs. Equations 3 and 4 present the constraints on weights of outputs and inputs respectively such that they are positive. This is ensured by constraining outputs weights (Equation 3) and input weights (Equation 4) to be greater than ε , an infinitesimally small positive value.

Input variables for DEA in public transport typically include physical and financial resources required to operate the system while output variables typically include variables measuring the service supply and its usage (Daraio et al., 2016, Jarboui et al., 2012). For the current research, vehicle capacity and daily mileage of the vehicle are considered as input variables while the daily ridership and revenue are considered as the output variables.

$$\max h_{j_0}(u,v) = \frac{\sum_{r=1}^{s} u_r y_{rj_0}}{\sum_{i=1}^{m} v_i x_{ij_0}} \qquad 1$$

$$\frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \leq 1 \quad , \quad j=1,2,\ldots n, \qquad 2$$

$$\frac{u_{rj_0}}{\sum_{i=1}^{m} v_i x_{ij}} \geq \varepsilon \, , \quad r=1,2,\ldots,s \qquad 3$$

$$\frac{v_{ij_0}}{\sum_{i=1}^{m} v_i x_{ij}} \geq \varepsilon \, , \quad i=1,2,\ldots,m \qquad 4$$

3.2.2 Detailed analysis of bus operations

In addition to the comparative performance efficiency analysis, the performance of the formal bus system of the city is analysed in a greater detail to understand the key gaps in their operations and planning practices. Based on the analysis, the key indicators that contribute to developing an integrated public transport system are identified. The findings can provide valuable feedback to similar cities in India and also cities from other developing countries looking to integrate informal public transport services into the mainstream transit planning and policy processes.

3.3 Integrating bus and paratransit services: Bi-level approach for transit assignment and frequency optimisation

It was explained in literature review (section 2.3) and in the introduction of the current chapter that earlier approaches of integrating paratransit services as a feeder to formal public transport services have seen limited success. The current thesis identifies paratransit as an independent mode of shared transport offering services in parallel to the formal transit systems. Hence the integration of these two services is formulated as a Transit Network Frequency Setting Problem (TNFSP). Frequency setting is part of the tactical planning stage of public transport planning which is intended for short to medium range decision making on public transport services. The base route networks and travel demand are used to identify the optimal frequencies required to meet travel demands on various routes. It is acknowledged here that the paratransit services don't operate with fixed frequencies as in the case of bus services. However, estimating the frequency and fleet needs on various routes would still provide an in indicative volume of services required and when aggregated at the city level, this can provide policy inputs on the number of licenses to be issued for paratransit operations in the city.

3.3.1 Rationale and formulation of the bi-level solution

As explained in section 2.4, solutions for TNFSP involve transit assignment to model the user's route choices in a multimodal network and frequency optimisation to meet the travel demand. Solutions for such a problem typically adopt either a single level formulation where transit assignment and frequency optimisation are solved together or a bi-level formulation which models transit assignment in the lower level and route wise frequency optimisation in the upper level. The bi-level formulation was identified as the better alternative for the current problem due to the following reasons:

i) Transit assignment solves for the user's route choice demands while frequency optimisation solves for the operators supply needs. These are often independent but conflicting objectives and hence a bi-level formulation allows for these two problems to be solved separately

ii) A bi-level formulation also allows to demonstrate the interaction between demand and supply explicitly by modelling the change in users' route choices as a function of frequency changes and vice-versa

Therefore, a bi-level optimisation approach with multi-modal transit assignment in the lower level and integrated frequency optimisation in the upper level was adopted for the current thesis.

The solution presented by Verbas and Mahmassani (2015) for a real-world case of integrated transit network frequency setting problem (TNFSP) using a bi-level formulation comes closest to the current thesis. The solution was formulated to derive headways that maximise wait time savings of users for 30 min intervals considering service patterns i.e. a subset of stops with the highest demand within a route subject to fleet, vehicle loading, budget and policy headway constraints. The transit assignment in the lower level is carried out using the multi-modal time-dependent user equilibrium for travel time hyperpaths. Therefore, both the levels of the solution were solved from the users' perspective. The paper compares two solution methods: a stand-alone method where the two levels are solved one after the other and an integrated method that solves both levels iteratively until the problem converges. It was observed that the results between the two approaches were comparable and that the stand-alone approach is more suited for short to medium range decisions while the integrated approach was more suitable for long-range decisions.

The current thesis adopted the stand-alone bi-level modelling approach proposed by Verbas and Mahmassani (2015) given our short to medium range focus. However, the formulations for transit assignment and frequency optimisation were altered to reflect the needs of the current problem. While Verbas and Mahmassani (2015) solve both the levels of problem from the user's perspective we solve the transit assignment problem in the lower level from the users perspective and the frequency optimisation problem in the upper level from the operators' perspective. Additionally, we carried out the transit assignment for the peak hour of the day for the entire route network with the objective of minimising users' travel time through the user-equilibrium method compared to the 30 min intervals and for service patterns i.e. only a group of stops. This is to understand the route-wise maximum demand. The frequency optimisation problem in the upper level was solved using the maximum load section method proposed by Ceder (1984) and Hadas and Shnaiderman (2012) as against the wait-time minimisation approach adopted by Verbas and Mahmassani (2015). Optimal route-wise frequencies were derived such that they meet the demand on the maximum load section. Minimising cost of operations was selected as the objective function with fleet availability, meeting demand on various links and policy headways as the constraints.

Further, the output from the optimisation exercise were used to quantify the impact of the optimised public transport system on the society. Congestion and air pollution are two key impacts of the public transport system on the city (Sen et al., 2010). Therefore, the road space requirement and emissions caused by various mixes of public and paratransit systems have been quantified to measure the impact of alternative mixes of public transport services on the city. Various alternative scenarios of the user demand and transit supply were tested to assess their impacts of alternative mixes of public transport and paratransit supply on the society.

Figure 5 presents a summary of the proposed solution framework for the current thesis. The inputs and outputs of both the levels are indicated in the figure. The model in each level starts from the input data point and ends with the outputs generated in each stage.

The integrated transit assignment in the lower level and frequency optimisation in the upper level together cover objective iii of the thesis listed in section 1.4.1 i.e. developing a multimodal framework for frequency optimisation while incorporating travel demand needs of users. The analysis of alternative demand and supply scenarios explained in section 3.5 estimate road space requirements and emission implications of each scenario thereby covering objective iv i.e. to quantify impacts of alternative public transport development scenarios and to recommend a way forward. In summary, the bi-level optimisation combined with the public transport scenario analysis covers the objectives of the users, operators and the society.

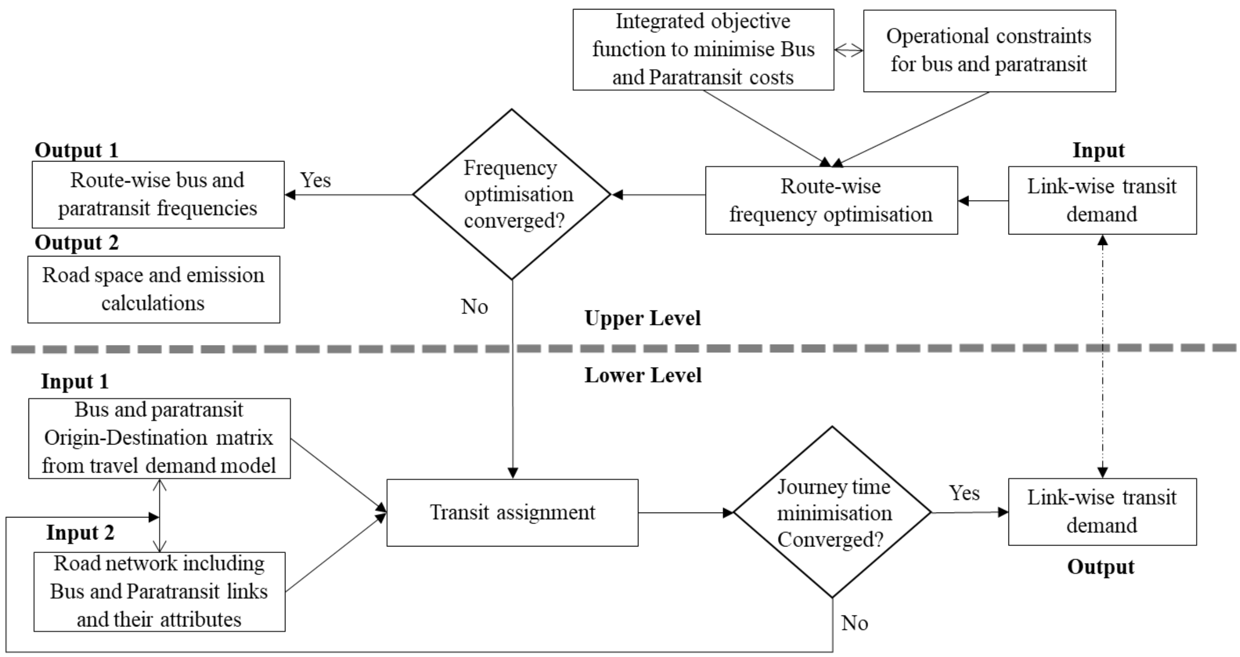


Figure 5 Bi-level model developed for transit assignment and frequency optimisation

3.3.2 Solution methodology for user equilibrium based transit assignment

The transit assignment problem was solved based on the methodology proposed by (Ortuzar and Willumsen, 2014) using the traditional four-stage travel demand modelling technique. The travel demand data for the model was derived from the household survey based travel behaviour analysis explained in section 3.1. The city level mode shares were used to derive baseline bus and paratransit demand within the overall travel demand. The current study focuses on relative preferences of bus and paratransit services. Therefore, binary logit based mode choice models were developed to estimate mode shift scenarios between these two modes (iTrans, 2014a).

We carried out an integrated bus and paratransit assignment in TransCAD-the travel demand modelling software. In TransCAD-the conventional private vehicle assignment uses standard link speeds for all vehicle types, while public transport assignment differentiates the links into access links, public transport links and stops. However, paratransit services don't follow fixed passenger stops and instead stop anywhere along the route based on user needs. Hence the traditional TransCAD public transport assignment process has been adapted for the current context where we coded the network characteristics of both bus and paratransit services.

Since bus and paratransit have different network coverage, the access links and service links have been adequately coded into the network attributes for both the modes. The links speeds and capacities have been updated accordingly. These attributes were used for transit assignment thereby ensuring that it isn’t the same as private vehicle assignment. Such an integrated bus and paratransit assignment in a traditional travel demand modelling environment is one of the contributions of this thesis to current literature.

The public transport network comprising of bus and paratransit services was additionally coded into the overall city road network. Since bus and paratransit have different network coverage, the access links and service links have been adequately coded into the network attributes for both the modes. Network attributes like link speed, passenger capacity etc. were calculated accordingly to ensure that the transit assignment doesn’t use the link level speeds used for private transport assignment.

Figure 6 presents an overview of the methodology adopted for the current study. TransCAD 6.0, a commercial software package for Geographic Information Systems (GIS) based travel demand forecasting was used to carry out a multi-modal user equilibrium traffic assignment of bus and paratransit trips on to the road network. Table 8 summarises the data sources for various input parameters required for the TransCAD model. The step by step procedure followed to carry out the transit assignment for the case city is explained in Chapter 6.

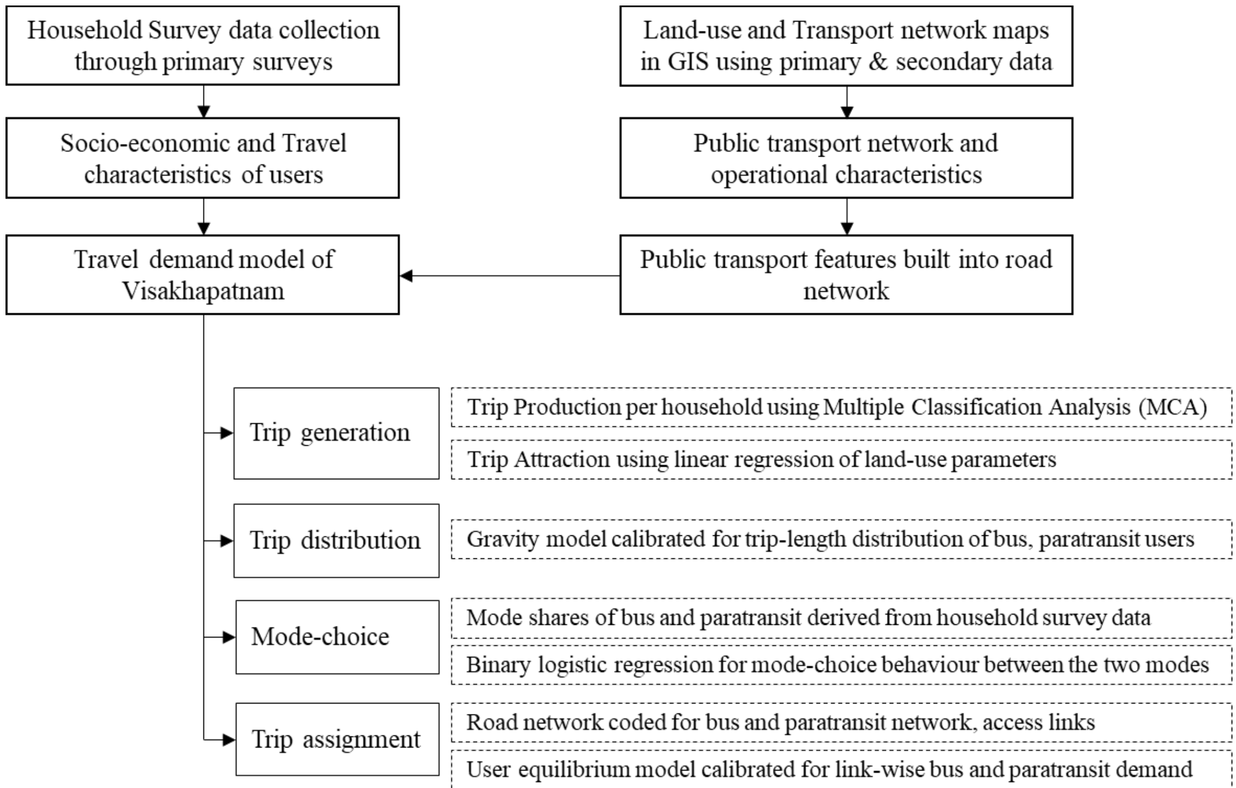


Figure 6 Flow chart for developing the travel demand model of Visakhapatnam

Table 8 Modelling components and input sources

Model component	Input data source
Traffic Analysis Zone (TAZ) map	Derived from the municipal ward map of Visakhapatnam
Road network	Derived from property tax data, Secondary data collected for road inventory, link speeds and road widths
Trip production patterns	Household interview data
Trip attraction patterns	Land-use data from master plan and Building wise usage type from property tax database
Trip distribution	Trip length distribution patterns for each mode derived from household survey data to calibrate the gravity model

Base mode shares	Bus and paratransit shares derived from household survey data
Traffic assignment	Traffic volume counts used for network calibration

Transit network representation

As explained in the literature review (section 2.4.3) a frequency based assignment was identifies to be more appropriate for an integrated bus and paratransit assignment, as paratransit doesn't adhere to a fixed schedule. The network representation for such an assignment is typically done in the form of transit stops and links (Fu et al., 2012, Verbas and Mahmassani, 2013). In case of the current study, the bus network has clearly defined bus stops, but the paratransit services pick-up and drop-off passengers anywhere on their routes according to passenger preference and not at predefined stops. It is therefore inaccurate to define a finite set of stops for the paratransit trip assignment. While individual paratransit vehicles do not even adhere to a fixed route, it was observed that the overall network of paratransit services are offered broadly on a few high demand routes of the city (iTrans, 2014a). Therefore, the paratransit services are also represented as routes for the purpose of frequency operations.

Therefore, we used the approach presented in Grosfeld-Nir and Bookbinder (1995) where the public transport network was defined as a set of segments having the same demand. The links along the existing road network of the city having access to bus and paratransit services are defined as transit segments while the rest are defined as access and egress links. The links speeds and travel times are defined accordingly and used for assignment. The drawback of such an approach is that the waiting time of users at the stops cannot be derived explicitly from transit assignment. However, the transit network speeds are calibrated in such a way that the journey time of users is similar to their real travel time collected from the personal interview surveys. The wait time proportions collected through the personal surveys were built into the transit network assignment.

The output of the assignment i.e. the link-wise equilibrium flows of both the modes were used as the input for the upper-level model solving for optimal frequencies of various bus and paratransit routes. The link-wise flows were initially split equally among all the bus and paratransit routes on the link and were later re-distributed based on the frequency optimisation formulation.

3.3.3 Integer Linear Programming (ILP) formulation for frequency optimisation

The upper level of the bi-level problem i.e. the Transit Network Frequency Setting Problem (TNFSP) was formulated in such a way that it can solve for the frequencies of multiple public transport modes plying on the network simultaneously. An integer programming (IP) formulation with the objective of minimising the total cost of public transport operations was adopted. Optimal frequencies were derived for the peak hour of the day, similar to the transit assignment, to derive the maximum fleet demand for the city's public transport demand. Meeting the demand on the maximum load section, fleet size and policy headways on each route are considered as the constraints. Equation 5 through equation 14 present the formulation of the frequency optimisation problem for a public transport network with i links and j routes.

ILP Problem Formulation:

- Minimise Total Operational Cost= (Cost/km) x (Route Length)x(Route Frequency)

$$Z = \sum_{i \in P j \in K} \boldsymbol{Cpkm_j} \, (\boldsymbol{L_j})(\boldsymbol{f_j}) \qquad 5$$

Subject to:

$$\sum_{i \in P j \in K} (\boldsymbol{f_{ij}})(\boldsymbol{R_{ij}}) \, (\boldsymbol{Cap})_{\boldsymbol{j}} (\boldsymbol{LF}) \geq \boldsymbol{D_i} \qquad \forall \, \boldsymbol{i} \in \boldsymbol{P} \qquad 6$$

$$If\ \boldsymbol{R_{ij}} = \mathbf{0}, \boldsymbol{f_{ij}} = \mathbf{0} \qquad \forall \boldsymbol{i} \in \boldsymbol{P}, \boldsymbol{j} \in \boldsymbol{K} \qquad 7$$

$$\boldsymbol{f_j} \geq \boldsymbol{f_{ij}} \qquad \forall \boldsymbol{i} \in \boldsymbol{P}, \boldsymbol{j} \in \boldsymbol{K} \qquad 8$$

$$\boldsymbol{f_j} \geq \boldsymbol{Pf_j} \qquad \forall \boldsymbol{j} \in \boldsymbol{m} \qquad 9$$

$$\sum \frac{\boldsymbol{f_j}\left(\boldsymbol{LT_j} + \left(\mathbf{2} \times \mathbf{60} \times \frac{\boldsymbol{l_j}}{\boldsymbol{S_j}}\right)\right)}{\mathbf{60}} \leq \boldsymbol{M} \qquad \forall \boldsymbol{j} \in \boldsymbol{BR}, \boldsymbol{j} \in \boldsymbol{K} \qquad 10$$

$$\sum \frac{\boldsymbol{f_j}\left(\boldsymbol{LT_j} + \left(\mathbf{2} \times \mathbf{60} \times \frac{\boldsymbol{l_j}}{\boldsymbol{S_j}}\right)\right)}{\mathbf{60}} \leq \boldsymbol{N} \qquad \forall \boldsymbol{j} \notin \boldsymbol{BR}, \boldsymbol{j} \in \boldsymbol{K} \qquad 11$$

$$\boldsymbol{f_j} \geq \mathbf{0} \qquad \forall \boldsymbol{j} \in \boldsymbol{K}, \text{integer} \qquad 12$$

$$\boldsymbol{f_{ij}} \geq \mathbf{0} \qquad \forall \boldsymbol{i} \in \boldsymbol{P}, \boldsymbol{j} \in \boldsymbol{K}, \text{integer} \qquad 13$$

$$\boldsymbol{R_{ij}} = \mathbf{0}, \mathbf{1} \qquad \forall \boldsymbol{i} \in \boldsymbol{P}, \boldsymbol{j} \in \boldsymbol{K} \qquad 14$$

Where:

Z = Total cost of public transport operation

$Cpkm_j$ = Cost per km of operation on route j

L = Route length

i = Links on the public transport network

j = Routes on the public transport network

P = Total number of public transport links in the road network

K = Total number of routes in the public transport network

f_{ij} = Assigned frequency for link i on route j

LF_j = Load factor of route j

Cap_j = Capacity of vehicle operating on route j

R_{ij} = Availability of route j on link i

D_i = Public transport demand on link i

f_j = Peak hour frequency of route j

Pf_j = Policy headway on route j

l_j = Length of route j

S_j = Average speed of route j

LT_j = Lay-over time of route j

BR = Bus routes within the public transport network

M = Total bus fleet available

N = Total paratransit fleet available

Objective function and decision variables: The objective function presented in equation 5 is a summation of the total cost of public transport operations (Z) across various transit modes i.e. bus and paratransit, calculated as the summation of the cost of operation of all routes. The route-wise frequency requirement during the peak hour (f_j) is considered as the decision variable. Since the optimisation is being carried out only for the peak hour, the multiplication of frequency and route length determines the vehicle-km operated during the hour. Therefore, the objective function for cost of operations was represented as the multiplication of the operational cost per-km of each route ($Cpkm_j$), the length of route (L_j) on which it operates and the peak hour frequency of the system (f_j). The cost per km is taken by route such that the variation in operational cost of bus and paratransit operation will be factored into the calculations as a function of the route under consideration.

Demand Constraints: Equation 6 presents the demand constraint i.e. the combined capacity of all the routes on the link should meet the desired transit flow derived from assignment in the lower level solution. It assigns frequencies to the route on each of its links such that the combined capacity offered all the routes on a particular link together meet its total travel demand. The total route capacity on a link is calculated as a multiplication of the frequency of each route on the link (f_{ij}), capacity of each vehicle (Cap_j) and its load factor (LF_j) i.e. the desired number of passengers on-board the vehicle vis-à-vis its capacity. The summation of capacity carried out across all routes should be greater than or equal to the total demand on the link (D_i). The null constraint (R_{ij}) in Equation 7 ensures that link-wise frequencies for a route (f_{ij}) are not assigned for the links where the routes are not operational, thereby not including those links in this calculation. Such a formulation allows for assigning different vehicle capacities and load factors to different routes thereby allowing for modelling multiple transit modes providing parallel services on a link.

Identifying the maximum load section: The current solution adopts the maximum load section method maximum load section method proposed by (Ceder, 1984) and (Hadas and Shnaiderman, 2012) i.e. the link assigned with the maximum transit demand/ flow needs to be identified for each route. The transit assignment in the lower-level on each link, which contains multiple routes passing through it. Therefore, a three-step iterative method is adopted to solve this problem:

Step 1: Initially, the flow assigned to each link is distributed equally among all the bus and paratransit routes passing through it. Based on the vehicle capacity on each route, the frequency requirement for the route is determined for this demand. Therefore, each link of the route has different initial frequency based on its share of the link flow

Step 2: Equation 8 then selects the maximum load section by comparing the frequencies across all links of the route (f_{ij}) and assigns them as the frequency for the entire route (f_j)

Step 3: The frequencies (fj) of various routes are then re-adjusted using equation 6 i.e. to ensure that the summation of capacity offered on the link is greater than or equal to the flow assigned to it

Ensuring policy frequency: A formal public transport system is required to provide a minimum level of service on all routes, irrespective of the demand, known as the policy frequency or headway. Equation 9 gives the policy headways for each route (Pf_j) i.e. the minimum frequency to be assigned to the route (f_j). For the current thesis, the policy frequency for buses was derived from secondary data while for paratransit, it was considered as zero, as they currently do not have any service obligation to the city

Fleet availability constraints: Irrespective of the demand and level of service requirements, the available fleet with each system determines its maximum service capacity. Therefore, equations 10 and 11 are introduced to represent the fleet availability constraints for bus and paratransit systems respectively. The fleet size required to provide for the assigned frequencies are estimated based on the round-trip times for various routes. The round trip time is calculated as the sum of time taken to complete the onward and return trips, and the lay-over time between the onward and return trips. l_j and S_j represent the distance and speed of various routes (j), while LT_j represents the lay over time of each route (j). M and N represent the maximum fleet availability of bus and paratransit fleets respectively. Equation 10 uses the round-trip time calculation to introduce capacity constraint for bus routes (BR), while equation 11 considers paratransit capacity constraints on routes beyond bus routes i.e. the paratransit routes.

Ensuring non-negativity: Equations 12 and 13 represent the non-negative and integer nature of link and route level frequencies while equation 14 represents the binary nature of parameter R_{ij} that indicates the availability of a route on a particular link.

In summary, equation 6 and equation 8 iteratively solve for the optimal route-wise frequency for minimising the cost of total operations while meeting the link-wise demand, maximum load section, policy frequency and fleet constraints.

3.3.4 Indicators to measure the societal impact of alternative bus and paratransit mix scenarios

The bi-level solution method explained above solves for users' objective of travel time minimisation and operators' objective of operational cost minimisation to derive the optimal route-wise frequencies of bus and paratransit systems. In addition to the impact on users and operators, the operations of bus and paratransit services also have a societal impact in terms of the externalities they generate. As explained in section 2.4, solutions to TNFSP in literature have included the societal impacts into the objective function of the frequency optimisation problem i.e. only frequencies with optimal societal impact were assigned. The current thesis only includes operators objectives in the frequency optimisation formulation and measures societal impact explicitly. Such a formulation allows to test for alternative bus and paratransit scenarios. Two of the indicators proposed by Sen et al. (2010) have been developed to measure the societal impact of the proposed public transport system: the overall road space requirement of the combined public transport system and emissions caused by the public transport system:

i) **Total road space requirement of the public transport system**: This is measured as the total vehicle km operated by the public transport system. Since individual bus and paratransit vehicles occupy different space on road, their vehicle km are measured in multiples of equivalent Passenger Car Units (PCU). Even though the formulation allows for multiple vehicle types, only bus and three-wheeler based paratransit vehicles with a capacity of six passengers per vehicle were used for analysis, in line with the objectives of the current thesis. Therefore, each bus was considered as 3 PCUs, while each paratransit vehicle i.e. the three-wheeled auto-rickshaw is considered as 1 PCU (IRC, 1994b)

ii) **Emissions from the public transport system**: The air pollution impact of the public transport system is measured as a function of the Particulate Matter ($PM_{2.5}$) emissions caused by the system. The average age of the vehicles of bus and paratransit was derived from the sample data used for operational characteristics analysis. The average age was then adopted for the entire population and the emission factor for the considered vehicles and their ages was considered for further analysis. Standard $PM_{2.5}$ emission factors of 0.571 gm/km for buses and 0.109 gm/km for paratransit vehicles were adopted for the current analysis (Emissions, 2018). However, the formulation allows for adopting varying emission factors for fleets of different fuel types and emission factors.

3.4 Illustrative example: Transit assignment and frequency optimisation for a sample network

The application of the stand-alone bi-level optimisation approach presented above is explained in this section using an illustrative public transport network presented in Figure 7. It contains a public transport network with nine links and ten nodes, with each link having access to either a bus route or a paratransit route or both. The network has a total of four public transport routes including three bus routes and one paratransit route. The number of lines on each link indicate the number of routes passing through it. This network doesn't have any links without a bus or paratransit service and hence all the links are included for transit flow assignment and frequency optimisation. In case of a real world network, the links beyond the transit network are designated as access and egress links to transit, with their speed and travel time calculated accordingly.

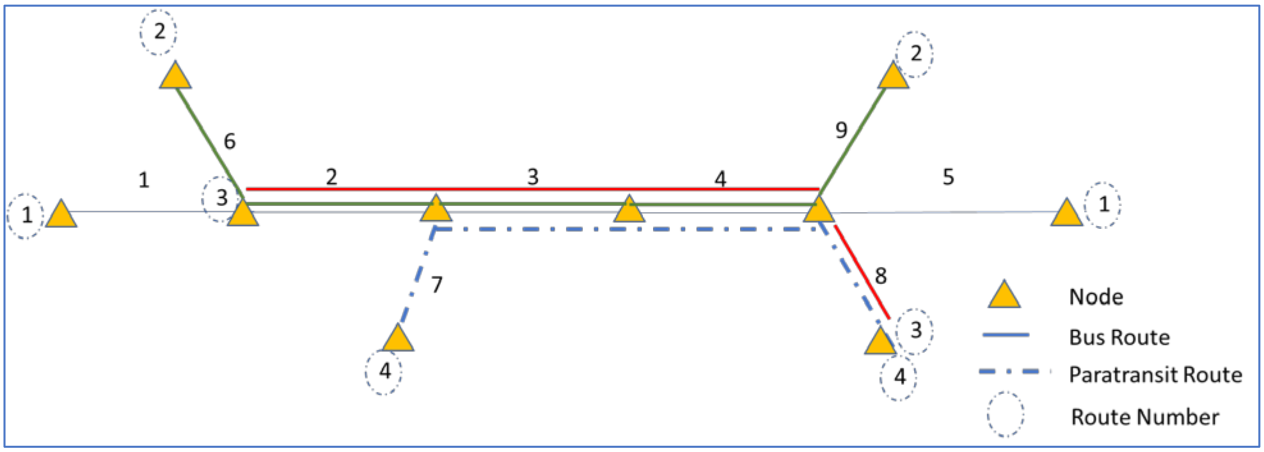


Figure 7 Illustrative public transport network

Table 9 Illustrative public transport network characteristics and link loads from transit assignment

Link ID	Link Length (km)	Speed (kmph)	Travel Time (min)	Route Exists (Yes/ No)		Route Number				No. of bus routes	No. of paratransit routes	Link capacity	Link flow
				Bus	Paratransit	1	2	3	4				
1	2	40	3.00	1	0	1				1	0	1500	1500
2	2	40	3.00	1	0	1	1	1		3	0	1500	1800
3	2	40	3.00	1	0	1	1	1	1	3	1	1500	2700
4	2	40	3.00	1	0	1	1	1	1	3	1	1500	1500
5	2	40	3.00	1	0	1				1	0	1500	1200
6	2	40	3.00	1	1		1			1	0	1500	600
7	2	40	3.00	1	0				1	0	1	1500	900
8	2	40	3.00	1	1			1	1	1	1	1500	300
9	2	40	3.00	1	1		1			1	0	1500	600

Table 10 Optimal frequencies for maximum load section and link-wise demand equilibrium

	Parameter		Link flow distributed across routes				Matching link demand and route frequencies			
	Route Number	Link flow	1	2	3	4	1	2	3	4
Link ID	1	1500	1500	0	0	0	25	0	0	0
	2	1800	1500	600	0	0	25	10	0	0
	3	2700	1500	600	60	900	25	10	1	180
	4	1500	1500	600	60	900	25	10	1	180
	5	1200	1200	0	0	0	20	0	0	0
	6	600	0	600	0	0	0	10	0	0
	7	900	0	0	0	900	0	0	0	180
	8	300	0	0	60	900	0	0	1	180
	9	600	0	600	0	0	0	10	0	0
Parameters for frequency and fleet estimation	Route Type		1	1	1	2	Objective function (Total cost of operations in Indian Rupees)= 11,480			
	Vehicle Capacity		60	60	60	5				
	RouteLength		54	36	18	6				
	Cost per km		20	20	20	3				
	Route Speed		40	40	40	40				
	Route Time		81	54	27	9				
	Layover Time		10	10	10	5				
	Round Trip Time (2 x Route time+ Layover time)		40	40	34	29				
	Optimal Frequency		**25**	**10**	**1**	**180**				
	Fleet required (=Cycle time X Frequency/60)		**17**	**7**	**1**	**87**				

The bi-level model explained previously was applied to this network, where the transit assignment of bus and paratransit trips was carried out in the lower level followed by the frequency optimisation solution in the upper level that takes link flows from assignment as input. The following is a step-wise procedure followed for applying the bi-level solution to this network.

i) **Coding for transit assignment:** Table 9 shows a sample attribute table of the road network that gives the details of link length, free-flow speed, travel time, length and the availability of various bus and paratransit routes on each link. A user-equilibrium based transit assignment for the Origin Destination (OD) matrix of bus and paratransit trips is conducted using user-equilibrium method in TransCAD 6.0. The OD creation and transit assignment stage is not illustrated here as we adopted the standard headway based methods which were well established in literature (explained in section 2.5.1). Table 9 and Table 10 present an overview of how the output from the transit assignment is converted into an input for optimisation.

Table 9 includes the results of the transit assignment and the coding on the routes plying through each of the links. The routes operational on the link are coded as 1 and the rest are coded as 0. Therefore, the summation of all 1's on a link gives the total number of routes playing through a link. Similarly, all the 1's in the column of a route indicate the links through which the route passes. In case of the network presented in Figure 7, the three bus routes are numbered from one to three while the paratransit route is numbered four. The link length, speed, travel time, capacity and the desired transit flow are also included in the table. The link capacity is a base capacity assumed for each link based on the network characteristics i.e. number of buses and paratransit routes passing through the link. Link flow is the desired transit demand on these links based on the 'user equilibrium' transit assignment that is converged for shortest journey time for users.

These attributes are used to assign transit OD matrix on to the network using the user-equilibrium method. The link-wise desired flows in congested travel time conditions are derived based on this and used as an input for the optimisation exercise.

ii) **Coding to convert link-wise transit demand to route level demand:** Table 10 gives an overview of how the link flows are split further to derive route level flows. This is further classified into two sections in the table:

a) The Link ID section of the table provides details of the route-link relationship and the frequency outputs from the optimisation exercise, wherein the links are considered in rows and routes in columns.

b) The 'parameters for frequency optimisation' section includes inputs required for the optimisation exercise i.e.

I. Route type: whether the route in each column is a bus or a paratransit route

II. Passenger capacity: the capacity of individual vehicles on the route as a function of the route type. The current research only deals with two vehicle types i.e. bus and paratransit. However, the same modelling framework can also be applied in cities with more vehicle types providing transit services

III. Route length, speed, travel time and layover time: These parameters are needed to determine the round trip time of vehicles operating across various routes. The total travel time for each route is derived by adding up the link-wise travel time across all links along the route. The travel time considered is the congested travel time on the links, derived after the user-equilibrium based transit assignment, derived from TransCAD

IV. Cost per km: We have considered the operational cost for the two modes under consideration. This is because the focus of the current research is to identify the optimal mix of transit modes purely based on operational aspects. Therefore other costs like manpower and infrastructure were considered as fixed costs, external to the current study. However, these can easily be incorporated into the model without altering the model if needed, by assigning the appropriate values.

V. Optimal frequency: Gives the output of the optimisation exercise i.e. the frequency of each route for which the overall cost of operations is minimised

VI. Fleet required: The fleet required on each route is determined as a function of the optimal frequency and the round trip time required for the vehicles operating on the route. If the round trip time exceeds one hour, the route will require additional fleet to maintain the designed frequency during all hours. This only derives the operational fleet required to be deployed on each route. The total fleet required in the city also involves estimating spare fleet requirement, depot allocation of fleet etc. which is beyond the scope of the current thesis.

c) **Frequency optimisation in CPLEX:** The total transit flow on a link is initially distributed equally across all the routes operating on it. The maximum load section on each of the routes is then derived by comparing the initial demand assigned to each link for various routes. Further, the frequency for the maximum load section is assigned to the entire route and flows on all the links of the route are updated to have the same demand as the maximum load section. The maximum required frequency to cater to this demand are calculated based on the capacity offered by the individual vehicles on these routes. The total frequency and fleet requirements of this scenario is matched with operators constraints like the total fleet available on each mode and policy headway i.e. the minimum headway required on each route. The frequencies across modes and routes are reallocated such that the objective function is re-calculated considering the available constraints.

d) **Using the transit assignment and optimisation outputs to measure societal impact**: The overall cost of public transport operations is derived as a measure of cost to the operator. Additionally, two more indicators to quantify the impact of the public transport mix on the city were derived from the outputs of the optimisation exercise. The road space requirements for the proposed service frequencies and particulate matter (PM 2.5) emissions from the vehicular exhaust of these services have also been derived. The road space required to operate the services is measured for the peak hour for a multiplication of the Passenger Car Unit (PCU) of the vehicle. The emission impact is derived using the standard emission factor for each vehicle type. Table 10 gives the output of such iterative analysis for the sample network presented in Figure 7. The objective function value i.e. the optimal total cost of public transport is also presented in Table 10.

These steps are carried out iteratively until the optimal frequencies and route wise link loads are achieved. The following is a summary of the procedure for converting link flows to route frequencies in a step by step algorithm.

3.4.1 Summary of algorithm for deriving route frequencies from transit flows

i) Derive link-wise transit flows through user equilibrium based transit assignment

ii) Assign link-flow to equally across all routes passing through it

iii) For each route, compare flows assigned to each of its links to identify the maximum load section

iv) Assign frequency to each route based on the link with maximum load while ensuring that the policy headway is maintained

v) Compare the total supply of buses on all routes of each link with the total demand on the link. Similarly, the frequency and travel time of each route is used to compute the total fleet required across all routes and is compared with the available fleet

vi) If the link-level travel demand and overall fleet constraints aren't satisfied, the frequencies in step iv are reassigned such that steps iv and v are iterated until both the constraints are satisfied simultaneously

vii) Once the link-level demand and total fleet requirement constraints are met, the results are used to compute the societal impacts in terms of the total road space requirements and emissions caused by bus and paratransit services

3.5 Alternative public transport demand and supply scenarios

The bi-level planning and frequency optimisation model explained in the previous sections presents an analytical framework to identify the optimal supply of formal and informal public transport systems for a city and its impact on the road space requirements and air pollution. The model is developed with the objective of identifying the optimal mix between formal and informal transit systems as the city's development pattern and hence the travel demand patterns evolve over time. Therefore, the following scenarios were tested to demonstrate how the model can inform decision making on public transport provision and its impact on the city. The scenarios were identified based on existing National and International policy commitments of India like the

National Urban Transport Policy (NUTP), Sustainable Development Goals (SGD) etc. such that recommendations from the current thesis can inform the discussion on these policies. The scenarios and modelling framework were designed in such a way that the findings for the case of Visakhapatnam can also inform other cities intending to integrate formal and informal transit systems

Scenario 1-Integrated planning scenario: Combined transit assignment and optimisation

The National Urban Transport Policy (NUTP) of India, 2016 and various subsequent policy initiatives like the Smart cities mission highlight the need for multimodal integration in transport (MoUD, 2006, MoUD, 2014). Towards testing the impact of such integration, in the first scenario, we model an alternative transit network where the entire public transport demand and supply network is considered as one system instead of the current practice of planning bus and paratransit as independent systems. The combined Origin-Destination (OD) matrix comprising of all the public transport trips i.e. formal and informal together, was assigned on to the public transport network which is the combination of all the bus and paratransit routes. The optimal frequency and fleet requirements for such a scenario, the overall cost of operations, the road space requirements of the system and its emissions were estimated.

Scenario 2-Demand shift scenarios: Increasing bus share of transit demand

In addition to the National level initiatives highlighted above, global initiatives like the Sustainable Development Goals (SDGs) and Sustainable Mobility for All (SUM4ALL) advocate for high shares of public transport systems in cities. This scenario analyses the impact of increasing the bus share of trips within the total public transport demand. It is known that trip length and travel time are key determinants of users' mode choice decisions and the travel patterns of Indian cities show that as city populations grow, their size and trip lengths also increase (Moser et al., 2016). In order to quantify the impact of such shifts on the public transport systems and the city the current scenario analyses a transit demand scenario, where the paratransit users travelling longer distances i.e. with trip lengths greater than 5km shift to buses. The impact of such a shift shifts were quantified through five sub-scenarios with each sub-scenario representing an incremental shift of 20% of the long distance paratransit services to buses. Separate transit assignment and optimisation are carried out for bus and paratransit networks to assess the impact of such a scenario on the fleet and road space requirements, cost of operations and emissions.

Scenario 3: Supply shift scenarios: Trunk and Feeder system for bus and paratransit

It was highlighted in section 2.3.2 that majority of the available literature on paratransit integration with formal modes focuses on designing them as a feeder to the main haul public transport system. Therefore, the third set of scenarios test for the implications of designing such a system. In these scenarios, the impact of buses providing trunk services on high demand routes and paratransit operating along the existing bus routes thereby providing feeder services to buses was tested. Additionally, two alternative supply scenarios i.e. the impact of providing only one of Bus or paratransit services to cater to the entire public transport demand in the city were tested.

Scenario 4: Mass Transit scenario: Bus Rapid Transit (BRT) along high demand corridors

Many cities in India and other developing countries are at various stages of developing bus based mass transit systems i.e. Bus Rapid Transit (BRT) systems, which provide exclusive right of way to buses. (ITF, 2018) suggest BRT based mass transit systems in Indian cities to improve the overall emission implications from transport. Therefore, this scenario tests for developing an open BRT system in the case city that retains the existing bus route network but increases their speed on the mass transit corridor by 25%. In addition to the road space and emission impact calculations, this scenario also demonstrates the applicability of the model even for a city network with a mass transit system.

In summary, the scenario analysis applies the bi-level optimisation model to test the impact of various demand and supply alternatives on the cost of public transport operations in the city, the road-space occupied in providing the public transport service and the emissions caused in the process.

3.6 Summary of methodology and key contributions to literature

This chapter explained the methodology adopted to fulfill various objectives set out for the thesis. Integrated planning for formal and informal public transport systems has received limited focus in literature as majority of paratransit literature focuses on its governance and operators' livelihoods aspects. Hence this thesis developed a novel framework for integrated formal and informal transit planning by adapting methods for formal public transport planning and incorporating key features of paratransit services into it.

The demand characteristics of the two systems were established based on detailed household survey data capturing socio-economic and travel behaviour characteristics of both the modes. To the best of our knowledge this is the only study to establish the relative characteristics of formal and informal transport users to this level of detail. We have also used these demand characteristics to carry out an integrated transit assignment in TransCAD to derive link-wise bus and paratransit demand. This required coding the supply characteristics of bus services with fixed stops and schedules along with paratransit services which typically provide high frequency services without predetermined stops. The framework for such integrated transit assignment for paratransit systems is another contribution of this thesis to the current literature.

The supply characteristics of the two systems were established through primary and secondary surveys and were later compared for performance efficiency using Data Envelopment Analysis (DEA). A DEA based efficiency comparision between formal and informal transit systems hasn't been attempted before. Such an approach will highlight the specific input and output variables leading to the difference in efficiency between the two systems, thereby providing crucial inputs to the planning process.

The integration between bus and paratransit services is modelled as a frequency setting problem i.e. intervening at tactical planning stage of public transport planning. Previous attempts for paratransit integration modelled them as a feeder service with limited success (Del Mistro and Behrens, 2015, Ferro et al., 2012). Hence we treat paratransit as an independent system offering parallel transit services and use a frequency setting approach to integrate the two modes.

A bi-level transit assignment and frequency optimisation model was developed to determine the ideal mix of formal and informal transit services to meet the overall public transport demand in the city. While bi-level frequency optimisation was attempted before, it's application to real-world situations were limited. A stand-alone bi-level solution method was used in this thesis enables to solve for real world cases. The lower level of the model carries out multi-modal transit assignment to minimise users travel time in the network. The upper level of the model takes the link-wise travel demand input from the lower level and carries out integrated frequency optimisation of bus and paratransit services to minimise their overall operating cost while meeting constraints on travel demand, policy frequency and fleet availability.

The outputs of the bi-level optimisation exercise are used to estimate the societal impacts of the multimodal public transport measured in terms of road space needs and emissions implications. Therefore, the methodology adopted for this thesis covers for users, operators and societal objectives while planning for integrated public transport systems. Given the often conflicting objectives of users and operators the proposed approach can help cities in rationale decision making while planning for integrated public transport. The same can be demonstrated using the scenario analysis to test alternative development pathways for the city.

4 Visakhapatnam as Case city, Data collection

This chapter introduces the characteristics of the case city adopted for the current thesis and the data collection methods adopted to capture the users', operators' and city related data required for further analysis. The data collected can be classified into three categories:

i) Household surveys for users' socio-economic and travel characteristics

ii) Route network maps of bus and paratransit services in the case city

iii) Operational characteristics of bus and paratransit services

The data collection methodology and sampling strategy for primary surveys are explained in the following sections.

4.1 Introduction of the case city-Visakhapatnam

The city of Visakhapatnam (also known as Vizag), a medium sized city located on the eastern coast of India, is taken as the case study. With a population of 1.73 million it is the largest city in the state of Andhra Pradesh (Census, 2011a). The current urban agglomeration of Visakhapatnam is spread over an area of 534 sq. km., of which the built-up area is only 166 sq. km. (iTrans, 2014b). The city has a significant network coverage of both city bus services and paratransit services. The population of the city and the presence of both formal and informal public transport systems make Visakhapatnam a representative case-study among the medium sized Indian cities with population between 1-5 million. Therefore, the findings from the city can offer learnings for integrated public transport planning in other such cities.

The city bus system of Visakhapatnam is owned and operated by the Andhra Pradesh State Road Transport Corporation (APSRTC). The bus system has a total fleet size of 670 standard urban buses operating across 133 bus routes assigned to four depots, out of which 83 routes operate entirely within the city limits while the remaining routes provide connectivity to the suburban areas. The paratransit services in the city comprises of approximately 28,400 three wheeled auto-rickshaws with two variants of passenger carrying capacity: nearly half the fleet having a seated capacity of three passengers and the remaining half having a seated capacity of six passengers (iTrans, 2014a).

4.2 Data collection for user characteristics using household interview surveys

Travel behaviour of individuals is based on their socio-economic characteristics like gender, age, income, vehicle ownership etc., their activity patterns through the day and the corresponding travel needs (Koppelman and Bhat, 2006). Household travel demand surveys have been established as a reliable method to collect information on users' household characteristics as well as their activity and travel patterns. They also capture information of all the members of the household (Stopher and Greaves, 2007). Hence household surveys are used in the current study to derive the trip generation patterns of various user groups. We collected the household survey data presented in this study as a part of the preparation of the Low Carbon Mobility Plan (LCMP) of Visakhapatnam (iTrans, 2014a).

4.2.1 Sampling strategy for household surveys

A stratified sample of households that represents the various socio-economic groups in the city is selected for primary survey. The first step in determining the sample size is to know the total number of households in the city. Property tax is the largest source of tax revenue for the city municipal authorities in Indian cities. Hence they maintain a good record of all properties/ buildings existing in the city, the building footprint area and their land-use type i.e. residential, commercial, industrial etc. The Geographic Information System (GIS) based property tax database of the Greater Visakhapatnam Municipal Corporation (GVMC) maps provided the total number of households in each neighborhood of the city. This was further used to estimate the sample size for household survey (Xynthe, 2012).

A stratified sampling technique was used to determine the sample size of households in each municipal ward to represent the various levels of heterogeneity in the ward, including: population density of the neighbourhood, distance from the core of the city and income level heterogeneity. Figure 8 shows the map of households in Visakhapatnam mapped over the ward map for the city. The concentration of development in a few pockets of the city can be observed from the map. Some of the wards have high concentration of households while many have a space distribution, with seven wards having negligible inhabitation. Therefore, only 65 of the 72 municipal wards of the city covering the entire geographic spread of households in the city were selected for the household surveys. The other 7 wards are sparsely populated and hence have been left out of the survey. The following is the three-level stratification used for determining the sample size:

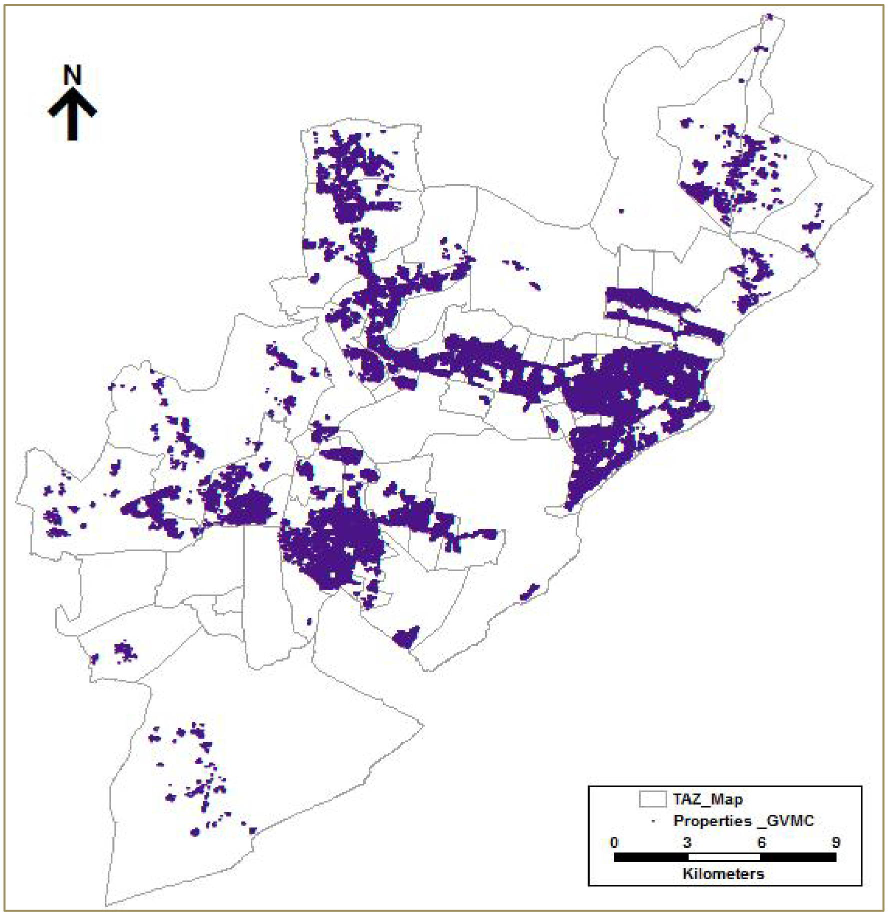


Figure 8 Property data overlapped with ward map of Visakhapatnam

(Source: GVMC, 2013)

i) **Estimating city level sample size for statistical representativeness**

The sample of households was determined in such a way that it is statistically representative of the total number of households in the ward. The total number of households in each ward were determined using the number of buildings under residential land-use in the property tax database. It was observed that the total number of households in the city was 4,19,343. The sample size for surveys was calculated based on probability sampling i.e. the central limit theorem states that samples greater than 30 in size tend to follow normal distribution irrespective of the size of the population.

According to this, considering a population of size **N**, mean **μ,** standard deviation **σ,** sample size **n,** sample mean **x** and if a normal distribution is assumed and a 95% confidence level is specified, this means that a maximum value of 1.96 would be Z $_{(critical)}$ accepted for the confidence interval (i.e. μ ± 1.96σ contains 95% of the normal probability distribution).

Using a standardized normal variable

$$Z = \frac{(x-\mu)}{\sigma / \sqrt{n}}$$

Assuming the error, (x- μ)=E, we get,

$$n = \frac{Z^2 \sigma^2}{E^2} = \left(\frac{Z\sigma}{E} \right)^2$$

If a 10% error is specified we would get, E= (x- μ) = 0.1 μ

Therefore, n= $((1.96/0.1)*(\sigma/\mu))^2 = 384* (\sigma/\mu)^2$

In Visakhapatnam, for the total households in all wards, Mean households per ward (μ)= 5699 and their standard deviation (σ)= 2572. Therefore, the minimum sample size for statistical representativeness of households ($n_{critical}$) at the city level is 1,885.

ii) **Ward wise distribution of sample size**

The total sample size derived above was distributed among the selected 65 wards in proportion to the total number of households in the ward. The sample allocated for each ward was then checked for statistical significance within the ward using a non-probability sampling test, as explained in (Biemer and Lyberg, 2003). Using this method it was observed that 1,885 households i.e. 0.44% of the total households in the city when distributed across all wards was too low to be statistically significant, in many wards. The GIS base data was used to observe the total number of households in each ward, out of which a statistically significant sample size of households was estimated for survey. On the basis of sample theory, size of sample for each of the wards was calculated and for a 95% confidence level (Biemer and Lyberg, 2003). Hence the total sample has been increased in such a way that all the wards have a statistically significant sample. Such a sample is needs 2,935 households i.e. 0.7% of total households in the city to capture the heterogeneity.

iii) **Representing the income level heterogeneity within each ward**

The sample size determined above was further distributed among various income groups of the ward, taking the property tax of a household as a proxy for its income. This is because the city of Visakhapatnam levies property tax as a function of the type of household and it's built up area. The city uses six different slabs of property tax which correspond to the type of construction of the household i.e. temporary settlements, ordinary tiled roofs, masonry tiled roofs, masonry terraced roofs, single storeyed Reinforced Cement Concrete (RCC) buildings and multi-storeyed RCC buildings.

It was assumed that higher income groups tend to stay in better and bigger houses thereby paying a higher property tax. Therefore, the proportion of households in each of these slabs was derived from the property tax data and used as an indicator of various income groups for the ward. The sample size estimated for each ward was also distributed in proportion to the number of households in each category. It is to be noted that property tax is only used to determine the sample size. All subsequent analysis regarding household income patterns was based on the primary data collected through the household surveys.

4.2.2 Household survey format

Table 7 presented the questionnaire used for the household survey. It captures general information about household and the information specific to individual in the household. The general information about the households includes information regarding the size of household, living conditions, assets owned and the demographics of all members of the household. Individual specific information of the questionnaire captures information related to individual age, gender, education, occupation and income along with their detailed existing travel dairy for the previous day. The detailed activity dairy and travel dairy of each individual included trip purposes, distances travelled, travel time, cost of travel and trip chain data to capture details for multi-modal use and included information like access and egress mode, distance, travel time and cost. The survey has been carried out manually through personal interviews at each household. The surveyors captured information for each member of the household that were answered either by the individual directly or by the head of the household.

4.2.3 Household survey methodology

The surveys were carried out between August and October, 2013 through personal interviews at each household, by a team of 25 well-trained surveyors. The surveyors visited localities of various income groups within each ward and selected households to be interviewed based on random sampling method. The questionnaires for each member of the household were answered either by the individual directly or by the head of the household and hence the accuracy of the information depended on their ability to recall all their trips. Therefore, it is likely that some of the shorter or less frequent trips of the members of the household were not reported during the survey. The data collected from households was later coded into spreadsheets for further analysis. Three levels of cross-checking were carried out to minimise the manual errors made during data entry. Data for some of the households were discarded due to incomplete survey forms and the 3,058 households which had the complete data were used for further analysis.

Given the sampling strategy that captured the heterogeneity of the households in the city, it can be reasonably assumed that the households covered through the survey were representative of the entire city. Additionally, some of the characteristics describing the surveyed individuals i.e. Age and Gender, for demographic profile and Vehicle ownership, for their income profile were compared with the data collected by Census of India to ensure that the collected data was representative of the users across the city (iTrans, 2014b). Table 11 presents this comparision taking household size i.e. number of inhabitants in each house as an indicator. The data from surveys has a similar pattern to that of the census data indicating that the sample survey data is representative of the entire population of Visakhapatnam. The detailed stratification of households adopted for the survey resulted in an accurate representation of both formal and informal transit users in proportion to their overall demand in the city. This further led to an unbiased analysis of their socio-economic and travel characteristics.

Table 11 Comparision of household size from household surveys with Census data

Household size	Census HHs	HH Interview HHs
1	3%	0%
2	12%	11%
3	20%	22%
4	38%	41%
5	16%	17%
6-8	10%	9%
9+	1%	0%

4.3 Developing the public transport network map of Visakhapatnam

The current thesis includes activities like comparing operational characteristics of bus and paratransit systems and transit assignment. Both these activities require the route network maps of the two systems as inputs, which are not available with any secondary source. Therefore a two stage approach was adopted to develop the public bus and paratransit network maps for Visakhapatnam:

i) Developing the base road network map of Visakhapatnam

ii) Mapping the bus and paratransit networks on to the road network map

4.3.1 Preparing the road network map of Visakhapatnam

The road network map of Visakhapatnam as developed by the Low Carbon Comprehensive Mobility Plan (LCMP) (iTrans, 2014a) is taken as the primary input for the current study. The LCMP divided the city into a total of 97 Traffic Analysis Zones (TAZs) i.e. zones with a relatively homogeneous land use development and travel demand patterns. The number of trips produced and attracted in the city are measured at the level of a TAZ. Therefore, each TAZ was represented by a centroid on the road network map i.e. the imaginary geographic centre of the TAZ from where the trips from and to the TAZ are originating or ending.

A road network with a total length of 3,469 km that included all the access and collector streets of the city along with the arterial, sub-arterial streets. The public transport network characteristics are summarised is Table 12. The street network is represented as links and nodes, where nodes represent the intersections and links represent the roads between intersections. This network is developed using Quantum GIS, an open source Geographic Information Systems (GIS) platform and included attributes of each link including the length and width of each street, average speed and travel time. Given the public transport focus of the current study, this network was refined to segregate the streets that have either bus or paratransit systems operating on them from the one's that don't have either of these services. The links with bus and/or paratransit were marked as public transport links while the rest of the network was marked as access and egress links to the public transport links.

The centroids of the TAZs are connected to the road network using centroid connectors, which are imaginary lines which are used for assigning the trips originating and ending at various TAZs on to the road network. As explained in section 3.3, the current thesis adopts a headway based assignment that defines the public transport network as a set of segments having the same demand. Therefore, the transit network only includes links but doesn't include any transit stops. Further, the smaller access links in the network were removed and only the access links directly connected to the public transport network were retained. Each TAZ was assigned four centroid connectors, to play the role of the smaller access and egress links. Figure 9 to Figure 11 present the various stages of extracting this network i.e. the TAZ map and road network used by LCMP of Visakhapatnam, the connectors providing access to the public transport in various zones and the road network containing public transport links.

Table 12 Key characteristics of the transit network map

Parameter	Bus	Paratransit	Network length	Percentage of network length
Links with availability of services	Yes	Yes	89	42%
	Yes	No	120.6	57%
	No	Yes	2.3	1%
Total bus Network			209.6	34%
Total paratransit Network			91.3	15%
Total Road Network			624.6	100%
Total public transport Network			211.9	76%*

Arterial and Sub arterial network in Visakhapatnam	278.4	

*-Network coverage within arterial and sub-arterials roads

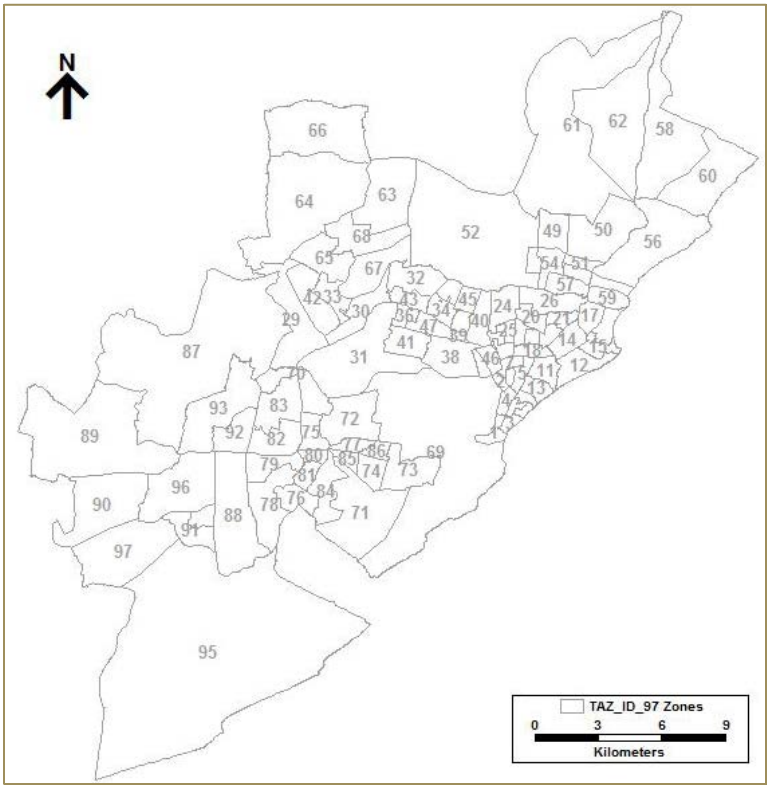


Figure 9 Traffic Analysis Zone (TAZ) Map of Visakhapatnam (LCMP Vizag)

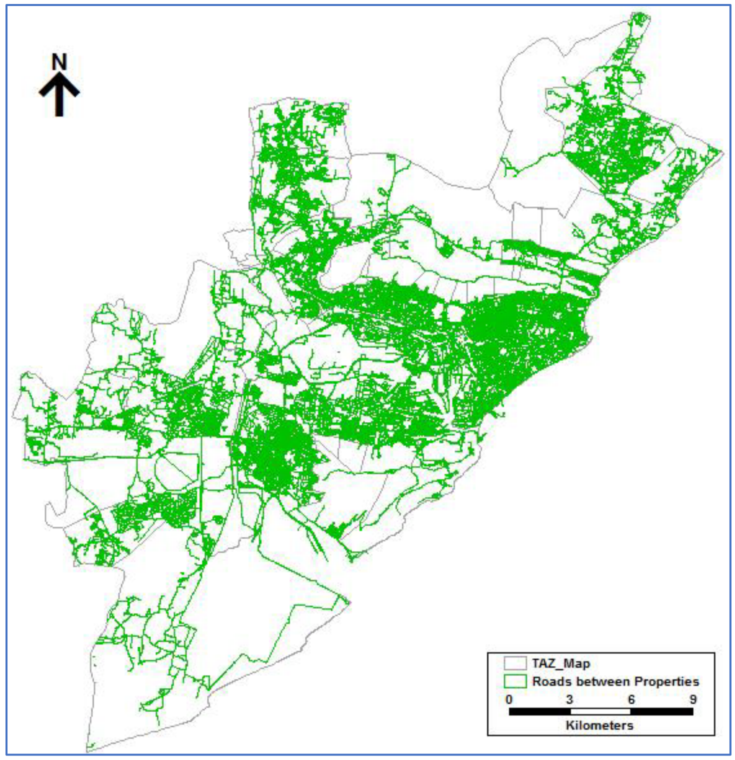


Figure 10 Total Road network of Visakhapatnam

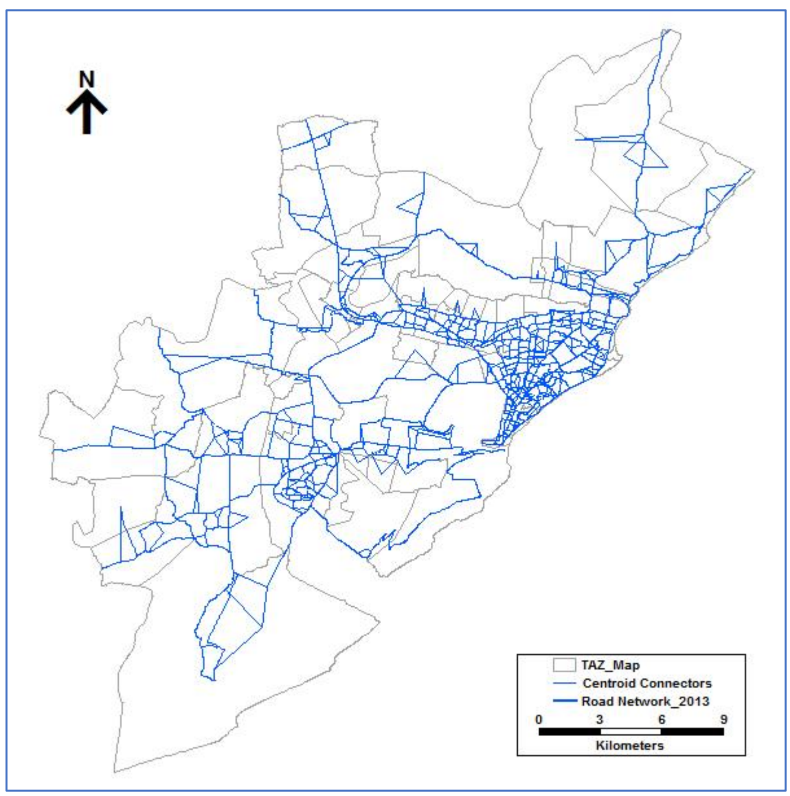


Figure 11 Transit network and connector streets of Visakhapatnam

4.3.2 Developing the transit attributes of the network

As noted above, the public transport network map for Visakhapatnam was developed for the city's mobility plan, which included planning for all modes of transport in the city. This included many small links to represent the entire road network. Given that the transit network has fewer intersections, the smaller links on the road network have been joined to aggregate them for bus and paratransit networks i.e. each node in the updated network represents the point where a bus or paratransit route enters or leave the corridor and the number of routes will remain constant throughout the length of the link. Further, the link attributes were developed based on those requirements. Given the transit focus of the current work, the network attributes of the transit links have been updated based on the travel time and link speed data of bus and paratransit services operating on these links, derived from LCMP 2014.

4.3.3 Mapping individual bus and paratransit routes

The network developed until now only includes the link-level characteristics like travel time and speed. Since the objective of the project is to optimise the frequency of each route, each individual route needs to be mapped to its corresponding link. This is necessary to carry out the transit flow conversion from link level demand to route level demand, as explained in section 3.4. The bus network and paratransit network-covering the six-seater shared auto-rickshaws which operate as informal public transport had to be mapped. The three-seater auto-rickshaw based services provide point to point taxi like services and are beyond the scope of the current project.

However, the network maps weren't available from secondary sources and had to be mapped for this study. The bus network map was plotted in google earth based on secondary data provided by APSRTC, for the alignment of the 103 routes operated the city. In case of paratransit, detailed consultations were carried out with individual operators and their trade unions to understand operational characteristics of the six-seater shared auto-rickshaw routes providing informal public transport services. In case of shared auto-rickshaws even though each vehicle doesn’t operate on a fixed route, it was observed that their overall operations in the city are aligned around a few high demand corridors. 18 such corridors were identified based on inputs from the paratransit operators and were mapped individually on google earth. These routes are exported as a kml (keyhole mark-up language) file and later converted to GIS files. Figure 12 represents the various steps involved in plotting the routes and exporting them to GIS.

The entire public transport network of 103 bus routes and 18 paratransit routes were mapped using this methodology. It was observed that out of the 103 city routes, only 92 operate totally within the city while the rest operate beyond the city limits for a majority of their operation. Even within these 92 routes, only 83 were considered in the later stages for frequency optimisation. This is because the remaining routes have a majority of their route overlapping with some other routes, only with a small variation at the source or destination, which is unlikely to change the overall analysis but has a significant implication on the time required to carry out the optimisation.

4.3.4 Connecting the road network and public transport routes

Finally, an attribute table connecting the road network and public transport routes was created with the road links as rows and bus and paratransit routes as columns. The cells in the table contained binary values i.e. the cells corresponding the links through which each route passes were marked as 1, while the rest of the cells were marked as zero. Similar coding was carried out across all routes to create a table linking the entire road and public transport network. All the cells containing ‘one’ in a row represent the various routes passing through the link. Similarly, all the cells containing ‘one’ in a column represent the links which that particular route passes through.

A similar attribute table is presented in section 3.4, for the illustrative example to demonstrate the methodology.

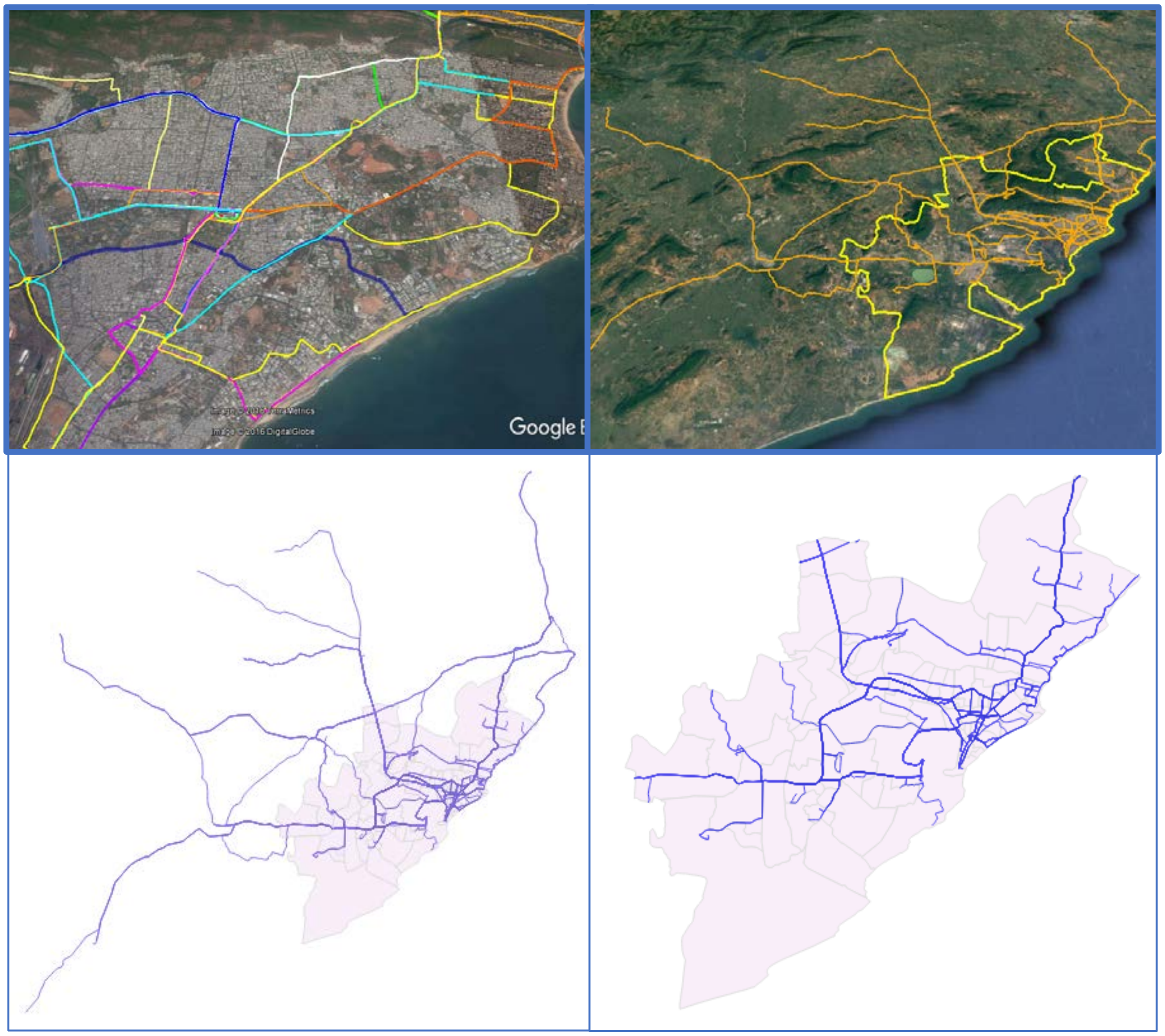


Figure 12 Mapping the public transport routes and merging them with the road network

4.4 Data collection for operational performance bus and paratransit

The previous sections explain the data collection for user characteristics and operators' characteristics to the extent of their network coverage. The current section gets into further detail of operational characteristics data collection including their hours of operation, daily km of service provided, ridership, financial performance etc. for the 92 bus routes and 18 paratransit routes explained in the previous section.

4.4.1 Bus operations data

The city bus system of Visakhapatnam is owned, operated and managed by the Andhra Pradesh State Road Transport Corporation (APSRTC), a state owned agency. The network planning, bus operations and fleet management of the system are carried out by the same agency. The data for the bus operations analysis was derived from the operations data maintained by the APSRTC. As presented in the literature review, the performance of a bus system needs to be measured through a wide range of indicators covering the physical operations of buses, passenger service attributes and safety of the services. However, APSRTC only maintains detailed indicators to measure the physical operational characteristics of buses like the mileage of operations and passengers travelled. The customer service and safety related indicators are not measured. Therefore, the current thesis only focuses on the physical operational performance of the Visakhapatnam city bus system.

APSRTC monitors the operational performance data of the city bus system at a daily and monthly frequency, disaggregated at the level of each route and depot. Operational performance data for the month of September, 2014 was shared by the operator for the current study. It was observed that the following key indicators were available for each of the routes: Length of the routes, route alignment, number of buses allocated to these routes, number of scheduled trips[1] per day, monthly mileage of the scheduled trips, mileage of trips that were operated according to the schedule, mileage of trips cancelled due to various maintenance and operational issues, aggregated

[1] Each trip refers to one round trip journey of the bus along its scheduled route of operation

revenue generated through ticket fares, revenue per km of operation, revenue per bus, average occupancy ratio i.e. the ratio of the demand generated along the routes and the capacity offered, daily vehicle utilisation, i.e., kilometres operated by each bus in a day. The analysis of this data is presented in section 1.1.

4.4.2 Paratransit operations data

The paratransit in the city comprises of approximately 28,400 three wheeled auto-rickshaws with two variants of passenger carrying capacity: nearly half the fleet having a seated capacity of three passengers and the remaining half having a seated capacity of six passengers. Each vehicle operates on its own either as a taxi service for individual trips or as a shuttle service providing shared mobility between fixed origins and destinations with high demand. Some vehicles switch between different modes of operation depending upon the demand at a given point in time. As a result, there exists no secondary data that captures their overall operations in the city. Therefore, two types of primary surveys were used to collect paratransit operational performance:

i) Questionnaire survey of paratransit operators

The data was collected through personal interview based questionnaire survey of 222 paratransit operators across the city through random sampling. The questionnaire for the survey included capacity of vehicle i.e. three or six seater, daily mileage or kilometres of operation, passengers carried, route(s) of operation, income and expenditure details of the operators.

ii) Road side occupancy surveys of paratransit

Additionally, the occupancy data for paratransit has been derived from road-side surveys conducted for the LCMP 2014, in addition to the operator surveys. The survey collected the number of people on-board various types of vehicles at various survey locations across the city and during various times of the day. Out of the overall dataset, the total sample of 682 pertaining to paratransit vehicles was used for the current thesis. The analysis of paratransit operations is provided in section 1.1, while their comparision with bus operations is presented in section 5.3.

4.5 Summary of data collection

This chapter explained the data collection carried out to implement the methodology proposed for the thesis. Visakhapatnam, a medium sized Indian was taken up as a case city and the data collection was carried out through primary and secondary data sources in the city. The city has a significant share of formal bus services and informal paratransit provided by shared auto-rickshaws, thereby providing a good case study for the proposed integrated planning framework.

User characteristics were collected using household surveys carried out at a statistically significant and representative sample identified through detailed stratification across the city. Operator characteristics of the formal bus services were collected from secondary data source while data on paratransit operations was collected through primary surveys. The operational network of the two systems was mapped on a GIS based road network which can be used as an input for travel demand modelling.

5 Analysis of user and operator characteristics

The analysis and findings of the data collected on public transport user and operator characteristics in Visakhapatnam are presented in this chapter. The analysis is categorised under the following sections:

i) Analysis of public transport user characteristics

ii) Analysis of operational characteristics of public transport

iii) Comparision between performance efficiency of bus and paratransit systems

iv) Review of city bus service planning practices of Visakhapatnam

5.1 Analysis of public transport user characteristics'

The primary surveys conducted in 3,058 households in Visakhapatnam collected activity and travel data corresponding to a total of 11,985 individuals living in these households. Details of the entire trip chain between the origin and destination of the individual were collected through the survey. Various key variables of these trips, including the purpose, weekly frequency, travel mode used, travel time spent and the length of each leg of the trip chain have been captured. In the case of a typical public transport trip chain, this included the access and egress legs of the trip, waiting time at the stop and the in-vehicle trip. It was observed that many public transport users haven't reported the waiting time details of their trips. Therefore, the 3,564 of the total public transport trips that had data for all the parameters was used for the comparative analysis of socio-economic and travel characteristics of individuals.

A per-capita trip rate of 1.61 trips per individual per day was reported for these households. The mode shares of all the trips reported during the survey are summarised in Table 13. Public transport trips i.e. bus and paratransit together form 27% of the total trips made in the city while the rest of the trips were made by Car, Two-wheeler, Bicycle and Walk. Bus trips comprised 18% of the city's trips while paratransit modes had a share of 9%. The presence of taxis in the city was negligible. The prominent share of bus and paratransit indicates their significant role in providing shared services to users. Hence, a detailed analysis of the user characteristics of both the modes was carried to understand the users' needs better such that the two systems scan be planned to retain the existing users and shift more users from private modes like cars and two-wheelers to public transport

Table 13 Mode share of trips in Visakhapatnam

Mode	**Share of total trips (in percentage)**
Car	2
Two-wheeler	16
Bus	18
Paratransit	9
Walk	52
Cycle	3
Total	**100**

5.1.1 Socio-Economic Characteristics of Bus and Paratransit Users

A summary of the key socio-economic variables collected through the household survey are presented in Table 14. Continuous variables like age and income have also been categorised into groups for the sake of presenting them in the table.

Age categories: Age was divided into four categories i.e. infants less than six years old, students-who typically age between six to eighteen, college students and working population-who age between eighteen to sixty years and elderly people aged more than 60 years

Income categories: The 'household income' variable received limited response during the surveys, due to the users' reluctance in sharing their income details.

Therefore, the interviewed households were categorised into high, medium and low income groups based on the living conditions of each household and the type of assets owned. According to this classification, the 3,058 households interviewed were divided into 542 low-income households, 1,263 middle income households and 1,252 high income households.

i) High income households: Living in multi-storeyed apartments or concrete structures and owning either at least a Car or the combination of a two-wheeler/ motorcycle and an Air-Conditioner (AC)

ii) Medium income households: Living in semi-permanent tiled roof households and masonry structures owning either a two-wheeler/ motorcycle or a refrigerator or an AC. Households living in concrete structure but without the assets mentioned above were also categorised as medium income groups

iii) Low income households: Living in temporary settlements or living in tiled roof buildings without the assets mentioned above

The variance between bus and paratransit users was measured using χ^2 test for categorical variables and t-test for continuous variables. Results show that all the variables show statistical significance at 95% Confidence Interval i.e. the socio-economic characteristics of bus and paratransit users are significantly different across all variables. Therefore, it can be inferred that bus and paratransit modes currently cater to users of different socio-economic characteristics. The observations specific to individual variables are explained below. The choice behaviour of various categories of users, between bus and paratransit is presented in the next section

Gender

It was observed that males formed a higher proportion of users among both bus and paratransit users. The share of female users was relatively higher in case of paratransit.

Age

Majority users of both bus and paratransit are in the age category of eighteen to 60 years. Users of higher age i.e. the one's older than 18 years are observed to have higher bus patronage while paratransit is more popular among the younger public transport users.

Occupation

Users engaged in formal employment like salaried jobs and college students form the majority users of buses followed by the school students and daily wage employees. In case of paratransit, school students form the single largest group of users, which is twice higher than the next group of users i.e. the employees engaged in the informal sector. The higher share of school students compared to bus users also explains the higher share of younger users among paratransit.

Household Income and Vehicle Ownership

The relative proportion of users between various categories of these variables is observed to be similar for bus and paratransit users.

Table 14 Comparision of Socio-Economic Characteristics of Bus and paratransit users

Variable	Classification	Bus	Paratransit	Total	χ2 test (Sig. Level)	t-test (Sig. Level)
Sample Size		3687	1882	5569		
Gender	Male	65%	57%	62%	0.000	
	Female	35%	43%	38%		
Age	<6	2%	8%	4%		0.000
	>6 and <=18	30%	36%	32%		
	>18 and <=60	65%	53%	61%		
	>60	3%	3%	3%		
Occupation	Formal employment	24%	11%	19%	0.000	
	Informal employment	15%	17%	15%		
	Self employed	3%	8%	5%		
	Household Work	10%	14%	11%		
	School Student	16%	37%	23%		
	College Student	30%	11%	24%		

	Unemployed	2%	3%	2%		
Household income	Low income	15%	17%	16%	0.030	
	Middle income	44%	43%	43%		
	High income	42%	40%	41%		
Car/ Two-wheeler owned	Yes	43%	46%	44%	0.005	
	No	57%	54%	56%		

5.1.2 Travel Characteristics of Bus and Paratransit Users

The summary of the variables measuring the travel characteristics of bus and paratransit users i.e. trip purpose, travel time and trip length is presented in Table 15. Even though these variables are continuous they are presented after categorising them into various groups. Paratransit trips were observed to be shorter and lesser in duration compared to bus trips. For a detailed understanding of the trip making behaviour of both the modes, various legs of the public transport trip i.e. the access and egress trips to and from the public transport stop, the wait time at the stop and the in-vehicle trip are presented separately. Access and egress stages along with wait times were established in literature as the weakest part of public transport trips and have the highest contribution to the total travel disutility (Krygsman et al., 2004). Therefore, Inter-Connectivity Ratio (ICR) i.e. the ratio of the total travel time spent on access and egress trips, including their wait times, to the total travel time has also been compared for bus and paratransit users.

The χ^2 test was used to measure variance between trip purposes of bus and paratransit users. As all other variables have continuous data, the t-test was used to compare the variance between the travel characteristics of users' of both the modes. Most of the travel characteristics are significantly different for bus and paratransit users, at a 99% Confidence Interval. The observations specific to each variable is given below:

Trip purpose

It was observed that buses have a higher share of the work trips, while paratransit has a higher share of education trips. This is consistent with the observations from the occupations of users of these modes presented in Table 14.

In-vehicle travel time

Majority of the paratransit users have a low in-vehicle travel time of less than 15 min, while for buses medium and longer distance trips form the majority. However, even within the bus users, 73% of the trips are less than 30 min long, which is an indication of the average trip times in the city being short.

Wait time

IPT users are also observed to have lower waiting times compared to Bus users. 62% of the paratransit trips have a waiting time shorter than 5 min indicating a very high frequency service. This is also a result of the paratransit trips being shorter than bus trips.

Access-egress travel time

It was observed that close to 84% of the access-egress trips for paratransit have a travel time of less than 10 min i.e. only users with origin and destination next to the paratransit services use the mode. Even in the case of buses, majority of users have a low access and egress time, but they also have a significant number of users in the longer time categories.

In-vehicle trip length

Paratransit users are observed to have a majority of their trips in the lower trip length categories i.e. trips shorter than 3kms, while Buses have a higher share among the longer trip length categories.

Access-egress trip length

Both bus and paratransit have majority of their users having a combined access and egress distance of less than 1 km. Buses have a slightly higher proportion of users accessing the system from a longer distance.

Inter-Connectivity Ratio (ICR)

The ICR i.e. the proportion of time spent on access and egress legs of the trips including wait times out of the total travel time has been analysed to understand the difference in trip patterns of bus and paratransit users in greater detail (Krygsman et al., 2004). Figure 13 presents the ICR patterns of both the modes. It was observed that paratransit users have a lesser ICR compared to bus users i.e. they spend lesser proportions of their trips on the access-egress and wait times. Conversely, as the ICR increases, users tend to shift towards buses.

Table 15 Comparision of travel characteristics of bus and paratransit users

Variable	**Classification**	**Bus**	**Paratransit**	**Total**	**χ2 test (Sig. Level)**	**t-test (Sig. Level)**
Sample Size		3687	1882	5569		
Trip Purpose	Work	44%	40%	43%	0.003	
	Education	50%	51%	50%		
	Shopping	3%	3%	3%		
	Others	2%	6%	4%		
In-Vehicle Travel Time	<15 min	27%	49%	35%		0.000
	15-30 min	46%	39%	43%		
	30-45 min	10%	5%	9%		
	45-60 min	11%	5%	9%		
	>60 min	6%	2%	5%		
Wait Time	<=5 min	32%	62%	38%		0.762
	5-15 min	64%	36%	58%		
	>15 min	4%	2%	4%		
Acc+Egg Travel Time	<=10m	50%	84%	61%		0.000
	10-20m	33%	9%	25%		
	>20m	17%	7%	14%		

In-Vehicle Trip Length	<1 km	8%	20%	12%		0.000
	1-3 km	18%	34%	23%		
	3-5 km	20%	19%	19%		
	5-10 km	26%	18%	23%		
	>10 km	29%	9%	22%		
Acc+Egg Trip Length	<=1km	92%	96%	93%		0.000
	1-3km	6%	2%	5%		
	>3km	2%	2%	2%		
Inter-Connectivity Ratio (ICR)	<=0.2	37%	76%	50%		0.000
	0.2-0.4	30%	10%	23%		
	0.4-0.6	24%	9%	19%		
	0.6-0.8	6%	4%	5%		
	>0.8 and <=1	3%	1%	2%		

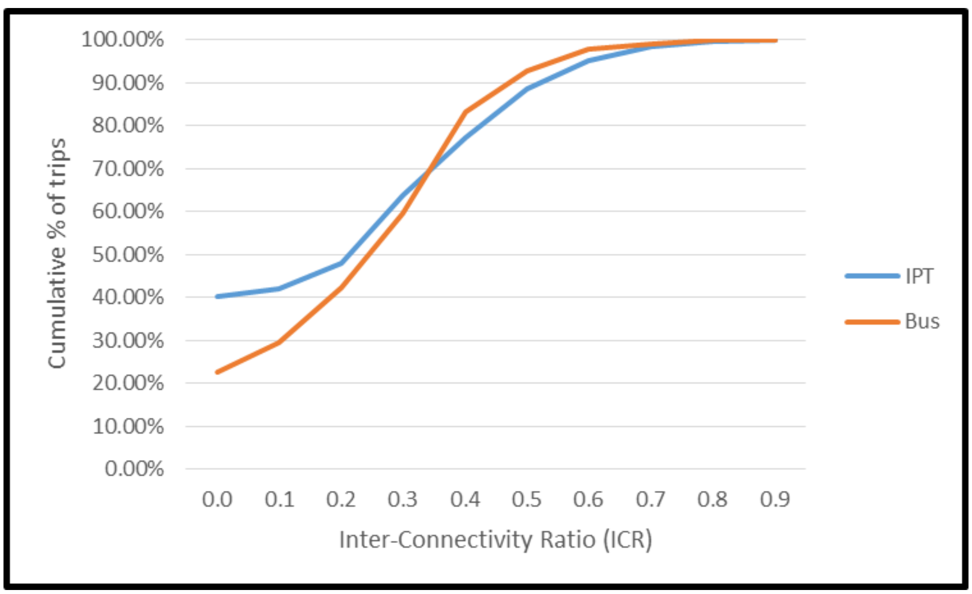


Figure 13 Inter-Connectivity Ratio comparision for bus and paratransit users

In summary majority of the socio-economic and travel characteristics of bus and paratransit users are significantly different. Therefore, it can be concluded that bus and paratransit modes are currently catering to users of different socio-economic classes and also different travel patterns.

Each mode has its own group of users and hence it is important that public transport planning takes cognizance of the users preference of both modes while planning for the public transport system.

5.1.3 Mode choice analysis between bus and paratransit

Given the significant differences in characteristics of bus and paratransit users, the key variables impacting their choice between the two modes was analysed through binary logistic regression. The choice of public transport mode was used as the dependent variable while the socio-economic and travel characteristics as independent variables. Before the logistics regression, the socio-economic and travel characteristics were separately checked for multi-collinearity. Table 16 presents the correlation matrix for socio-economic variables while Table 17 presents the correlation matrix for travel characteristics. Based on these results, 'vehicle ownership' variable among socio-economic characteristic and 'trip length' related variables among travel characteristics have been omitted from the logistic regression analysis.

Therefore, gender, age, occupation, income, trip purpose and the components of travel time i.e. the access and egress time, waiting time and the in-vehicle travel time were included in the model. For logistic regression, Buses were coded as 1, while paratransit is coded as 0. Gender has been coded as a binary variable with males coded as 1 and females as 0. Income, occupation and trip purpose have been coded as categorical variables, while the travel time components were coded as continuous variables. Both the correlation and logistic regression analysis were carried out using the software IBM SPSS 20.0.

Table 16 Correlation matrix for socio-economic characteristics

Variable	Parameter	Gender	Age	Occupation	Household Income	Car/ Two-wheeler owned
Gender	Pearson Correlation	1	0.205**	-0.349**	0.005	-0.020
	Sig. (2-tailed)		0.000	0.000	0.775	0.227
Age	Pearson Correlation	0.205**	1	-0.501**	-0.003	-0.008
	Sig. (2-tailed)	0.000		0.000	0.871	0.644
Occupation	Pearson Correlation	-0.349**	-0.501**	1	0.025	.034*
	Sig. (2-tailed)	0.000	0.000		0.137	0.043
Household income	Pearson Correlation	0.005	-0.003	0.025	1	0.079**
	Sig. (2-tailed)	0.775	0.871	0.137		0.000
Car/ Two-wheeler owned	Pearson Correlation	-0.020	-0.008	0.034*	0.079**	1
	Sig. (2-tailed)	0.227	0.644	0.043	0.000	
**. Correlation is significant at the 0.01 level (2-tailed).						
*. Correlation is significant at the 0.05 level (2-tailed).						

Table 17 Correlation matrix for travel characteristics

Variable	Parameter	Trip Purpose	Acc+Egg Trip Length	In-Vehicle Trip Length	Acc+Egg Travel Time	Wait Time	In-Vehicle Travel Time	Inter-Connectivity Ratio (ICR)
Trip Purpose	Pearson Correlation	1	0.329**	-0.037*	0.002	0.014	-0.017	-0.005
	Sig. (2-tailed)		0.000	0.026	0.910	0.409	0.318	0.786
Acc+Egg Trip Length	Pearson Correlation	0.329**	1	0.048**	0.463**	0.019	0.066**	0.360**
	Sig. (2-tailed)	0.000		0.004	0.000	0.247	0.000	0.000

In-Vehicle Trip Length	Pearson Correlation	-0.037*	0.048**	1	0.029	0.125**	0.494**	-0.146**
	Sig. (2-tailed)	0.026	0.004		0.080	0.000	0.000	0.000
Access+ Egress Travel Time	Pearson Correlation	0.002	0.463**	0.029	1	-0.008	0.009	0.837**
	Sig. (2-tailed)	0.910	0.000	0.080		0.644	0.609	0.000
Waiting Time	Pearson Correlation	0.014	0.019	0.125**	-0.008	1	0.098**	-0.146**
	Sig. (2-tailed)	0.409	0.247	0.000	0.644		0.000	0.000
In-Vehicle Travel Time	Pearson Correlation	-0.017	0.066**	0.494**	0.009	0.098**	1	-0.275**
	Sig. (2-tailed)	0.318	0.000	0.000	0.609	0.000		0.000
Inter-Connectivity Ratio (ICR)	Pearson Correlation	-0.005	0.360**	-0.146**	0.837**	-0.146**	-0.275**	1
	Sig. (2-tailed)	0.786	0.000	0.000	0.000	0.000	0.000	
**. Correlation is significant at the 0.01 level (2-tailed).								
*. Correlation is significant at the 0.05 level (2-tailed).								

Table 18 presents the results of the binary logistic regression analysis. The R^2 value of 0.198 which shows a decent fit for the model. It was observed that the variables-Gender, Income and the components of travel time exhibit the maximum correlation in the mode choice between bus and paratransit users. Variables like age and some of the occupations and trip purposes also have a significant correlation with mode choice. Since buses were coded as 1 and paratransit as 0, a positive coefficient indicates a preference towards with increase in the variables' value, while a negative coefficient indicates the opposite. Among the socio-economic variables, gender has a negative co-efficient i.e. females have a higher preference for paratransit while males have a higher preference for the buses. Even though age showed a significant positive correlation, the low value of its coefficients indicate that its relative impact is lower than the other variables. Within the occupation categories, only daily wage employees and the unemployed displayed a significant positive correlation towards buses i.e. they have a higher preference for buses compared to the formal employees. The other occupations do not exhibit significant variance compared to formal employees.

Amongst the trip purpose categories, trips in the 'education' and 'other' categories have a significant positive correlation compared to work trips indicating a higher preference for buses. It was observed that all the travel time components have a significant correlation to mode choice. The coefficients of all the travel time variables are positive indicating that paratransit is preferred for shorter trips. As the travel time increases, users tend to prefer buses more. Within the travel time components, waiting time at stops has the highest coefficient value implying that the frequency of services is a key differentiator in mode choice between bus and paratransit. Paratransit is preferred on the routes where it offers high frequency services. The preference for buses increases as their frequencies become comparable to paratransit.

The positive coefficients for travel time also indicate that as cities grow and their trip lengths increase, the likelihood of retaining and improving the public transport mode share in the city is critically dependant on improving the public transport network and it's frequency of service in such a way that the system meets the travel time requirements of its users. Therefore, it is necessary for cities to proactively monitor trip length patterns and provide bus and paratransit systems accordingly.

In summary, it can be concluded from the binary-logistic regression that choice between the public transport modes-bus and paratransit is explained best by the gender, income and travel time of the users. While the individual's age showed a significant correlation, its coefficient is low, indicating a lower influence on mode choice.

Table 18 Logistic regression analysis for bus and paratransit users

Variables in the Equation		Coefficient (B)	Standard Error	Wald-statistic	Degrees of freedom (df)	Sig.	Exp(B)	95% C.I. for EXP(B)	
								Lower	Upper
Gender		-0.422	0.113	13.987	1	0.000***	0.656	0.526	0.818
Age		0.007	0.004	2.769	1	0.096*	1.007	0.999	1.015
Household Income _Assets		0.241	0.063	14.79	1	0.000***	1.273	1.126	1.439
Occupation	Formal Employment (reference)			80.987	6	0.000***			
	Daily wage employees	0.604	0.297	4.143	1	0.042**	1.83	1.023	3.275
	Self employed	-0.162	0.296	0.301	1	0.583	0.85	0.476	1.518
	Household Work	-0.302	0.352	0.738	1	0.390	0.739	0.371	1.473
	School Student	0.031	0.303	0.011	1	0.918	1.032	0.569	1.87
	College Student	0.355	0.317	1.258	1	0.262	1.427	0.767	2.656
	Unemployed	1.089	0.308	12.485	1	0.000***	2.971	1.624	5.434
Trip Purpose	Work (Reference)			11.302	3	0.010**			
	Education	0.402	0.214	3.551	1	0.059**	1.496	0.984	2.273
	Shopping	0.252	0.232	1.178	1	0.278	1.286	0.816	2.026
	Others	0.709	0.241	8.644	1	0.003***	2.032	1.267	3.26
Access+ egress travel time		0.028	0.004	42.504	1	0.000***	1.028	1.02	1.037
Waiting time		0.135	0.012	130.395	1	0.000***	1.145	1.118	1.172
In-vehicle travel time		0.019	0.003	44.37	1	0.000***	1.019	1.014	1.025
Constant		-2.009	0.4	25.198	1	0.000***	0.134		
*** = P < 0:01; ** = P < 0:05; * = P < 0:1									
Note: Nagerkerke R^2 = 0.198									

5.2 Analysis of bus and paratransit operational characteristics

The household survey data has shown that Visakhapatnam has a significant presence of both bus and paratransit, with buses carrying 18% of the total trips in the city and the paratransit catering to 9% of the total trips in the city (iTrans, 2014b). This sections covers the operational or supply characteristics of the two modes while meeting this demand.

5.2.1 Network coverage of bus and paratransit services

The route network of the public transport modes in Visakhapatnam were mapped using secondary data sources, as explained in section 4.3. Figure 14 shows the road network map of Visakhapatnam marking the links having access to bus and paratransit services and Table 12 presents a summary of the network characteristics. The network characteristics including the length of each link, access to bus and paratransit services were coded as attributes into the GIS based network map of the city. The arterial and sub-arterial streets were identified from the LCMP. The total length of bus network was then derived by summing the lengths of all links having access to buses. The same process was used to derive the total road network length and the network length of paratransit services. The percentage of arterial and sub-arterial road network covered is derived using this data. road network length and network length of paratransit services for further analysis.

Buses have a network coverage throughout the city while paratransit routes were concentrated in the core area of the city with high travel demand. Out of the 624 km of arterial and sub-arterial roads in the city, approximately 201 km i.e. 32% of the road network has access to bus services. The paratransit services operate predominantly on only 91 km i.e. 15% of the city’s arterial and sub-arterial roads. While they may sometimes deviate to the remaining links depending on user requirement, these are observed to be occasional occurrences and hence are too uncertain to be considered within the core paratransit network for further analysis. All the links that have access to paratransit also have access to Bus services indicating the competition that exists between the two services.

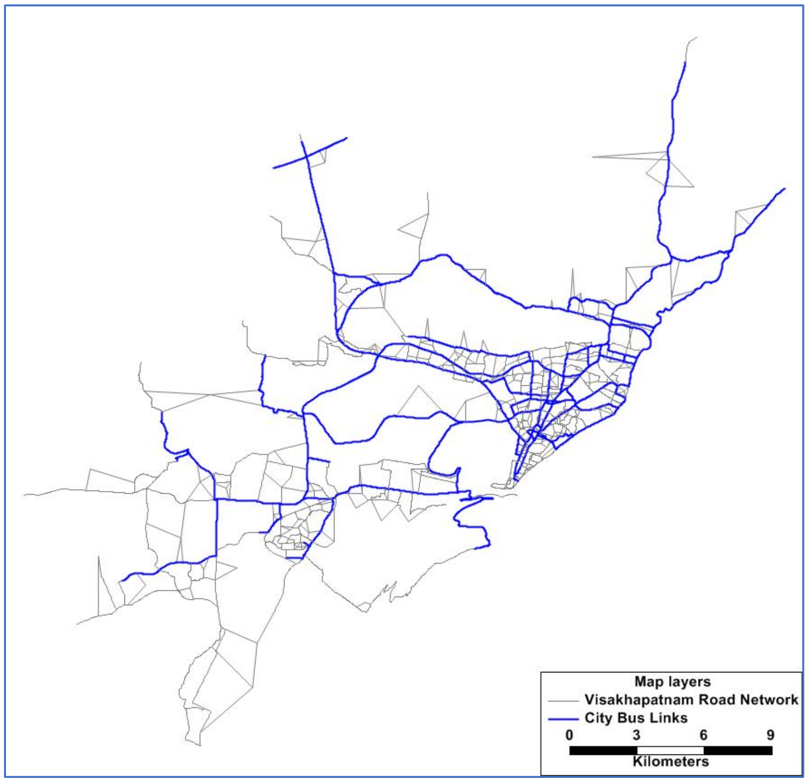


Figure 14 Bus links highlighted on the Visakhapatnam road network

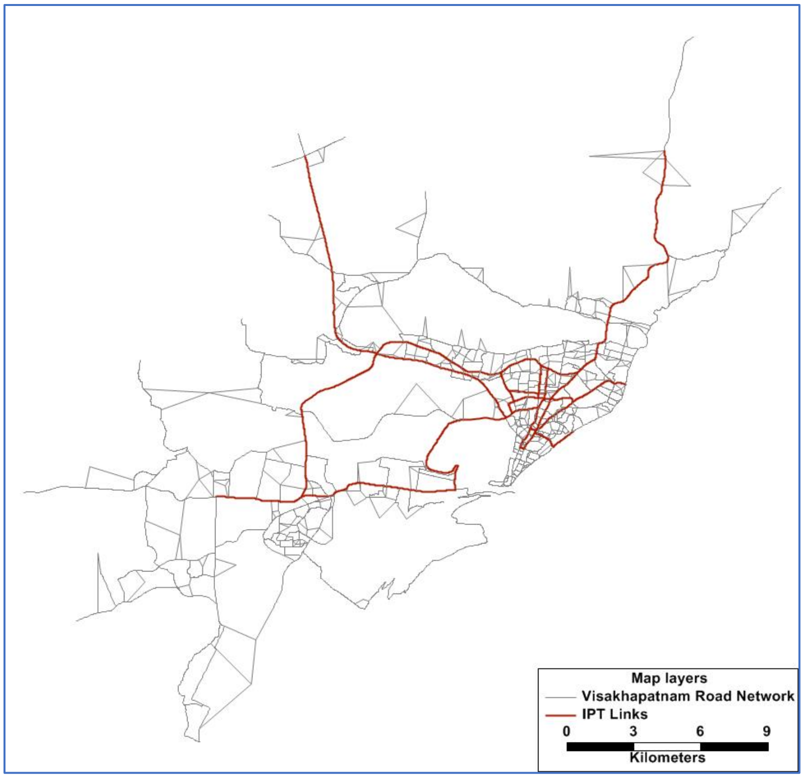


Figure 15 Paratransit (IPT) links highlighted on the Visakhapatnam road network

5.2.2 Bus operations analysis

The city has a total fleet size of 670 buses operating along 133 routes, operating from 4 depots, out of which 92 routes and 461 buses operate entirely within the city limits while the remaining routes provide connectivity to the suburban areas. A detailed analysis of these 92 routes was carried out to understand the operational characteristics of the existing bus system and the key factors that impact their efficiency.

Table 19 provides a summary of the key indicators used by APSRTC to monitor their operational performance. The descriptive statistics explain the current performance of the system against each of these indicators. These indicators capture information regarding the bus operations and their ridership. However, none of the indicators measure the travel characteristics of bus users like their trip lengths, travel times and origin-destination patterns. An occupancy ratio of 59%, daily passenger number of 891 and a monthly mileage of 8,864 are indicative of a well-functioning bus system when compared with many international bus systems (UITP, 2017).

Table 19 Descriptive statistics for Bus operations

Indicator	Units	Sample	Mean	Minimum	Maximum	Standard deviation
Route length	Km	92 routes	29.59	9	86	14.594
Route revenue per km	Rupees	92 routes	23.3	15.4	34.6	3.8
Occupancy Ratio	Percentage	92 routes	58.57	36.00	96.00	14.02
Vehicle-km per bus per day	Km	92 routes	310	218	420	42
Passengers per bus	--	92 routes	31.75	22	49	4.58
Passengers per bus per day	--	461 buses	891	323	1947	329
Vehicle km per bus per month	Km	461 buses	8864	3364	12665	1494

5.2.3 Paratransit operations analysis

The summary of operational characteristics of the 222 paratransit operators interviewed is presented in Table 20. Given the limited data from paratransit operators and the dynamic nature of their operations, data is analysed at the aggregate level i.e. macro indicators for the entire sample interviewed were derived as compared to the disaggregated route level analysis carried out for bus operations. The varied response rate for operator interviews and occupancy surveys led to the difference in their sample sizes.

The huge variation between minimum and maximum values of parameters like hours of operation and monthly km travelled indicate the uncertainty that exists in paratransit operations. Significant variations are also observed in their demand, with the maximum occupancy for some of the vehicles reaching 15 during peak hours. Even though the peak occupancy reaches 15, it is an outlier since the data had only three instances of 15 passengers per vehicle out of the total sample size of 682 vehicles captured in occupancy services. The mean (μ) and standard deviation of (σ) occupancy were 4.35 and 2.52 remaining that majority of the vehicles have an occupancy in the range of 1.83 (μ-σ) to 6.87 (μ+σ) i.e. 2 to 7 passengers (rounding off to the nearest whole number). Hence the maximum occupancy can be seen as an outlier and therefore is not assumed to have an impact on efficiency estimation of the system. Visakhapatnam has a mix of paratransit vehicles with 50% vehicles having a seating capacity of 3 passengers and the remaining 50% having a capacity of 6 passengers. Therefore, an average capacity of 4.5 passengers per vehicle was considered as the capacity of the vehicle. As a result, the observed average occupancy of 4.35 would put these services to be delivering an occupancy ratio as high as 97%.

Table 20 Descriptive statistics for paratransit operations

Indicator	Units	Sample	Mean	Minimum	Maximum	Standard deviation
Income/ Month	Km	217 operators	9025	1000	20000	3296
Hours of Operations/day	Rupees	222 operators	10.00	3	20	2.46
Passengers per vehicle	--	682 vehicles	4.35	1	15	2.52
Monthly mileage	Km	105 operators	1678	66	9069	1730

5.3 Comparison between efficiency of bus and paratransit operations

The findings from the analysis of bus and paratransit operations was used further to compare the relative efficiencies of the two systems. To understand the differences in the operational characteristics of buses and paratransit services, their key operational characteristics have been aggregated at the city level and presented in Table 21.

It was observed that buses carry more passengers per vehicle per day by providing assured service to the users all through the day. They operate with a service motive to provide assured access to mobility throughout the city, with their network coverage extending even to corridors where the demand does not make the operation commercially viable. On the other hand paratransit operators provide high frequency services during the morning and evening peak hours of the day on the high demand corridors of the city. As a result, they have a higher occupancy ratio and generate higher revenues even with lesser km of operation. Their smaller size and flexible nature of operations allows paratransit operators to quickly change routes according to changing demand patterns at various times of day and days of week.

Table 21 Summary of operational performance of Bus and Paratransit systems

Indicator	Bus	Paratransit
Number of routes	92	Dynamic
Hours of operation	16	10.4
Average vehicle capacity (passengers)	56	4.5
Monthly kms operated	8864	1678
Average occupancy (passengers)	33	4.35
Average occupancy (in percentage)	59%	97%
Passengers/vehicle/day	891	243

Revenue/vehicle/ month (in Rupees)	6952	8469
Network length (in km)	201	91
Percentage road length covered	32%	15%

The performance efficiency of the two systems was measured using Data Envelopment Analysis (DEA), where each bus route was considered as one Decision Making Unit (DMU) while for paratransit each vehicle was considered as one DMU since each of them follow their own routes within the 18 identified corridors of operation. An input oriented DEA with constant returns to scale was applied using MaxDEA, a free Microsoft access based application (Cheng, 2014). Table 22 presents the descriptive statistics of input and output variables used for their efficiency comparision. These variables were selected after matching recommendations from literature (Daraio et al., 2016) with the data available in Visakhapatnam. The data for buses is presented as an aggregate of the 92 routes, while in the case of paratransit the data covers 141 out of the 222 operators interviewed who reported all the input and output indicators used for efficiency analysis.

Input indicators measure the physical characteristics of bus services offered while output indicators measure the returns from the services offered, for the society and for the operator. The capacity offered by each vehicle and their daily mileage i.e. distance travelled per day, were identified as the key input variables to define the services on offer. The daily income/ revenue generated and the total passengers carried i.e. ridership achieved by the system are considered as the key output variables for the two modes. APSRTC only maintains ridership data in terms of daily average Occupancy Ratio (OR) i.e. total passenger kilometres divided by passenger km offered. This was converted to the passenger ridership using the vehicle capacity of 45 offered in the city. Bus services can also be measured using other input and output variables like crew deployed, fuel consumed etc. However, generating the same data for paratransit services is a challenging task. Therefore, we adopted variables defining the passenger capacity offered by the system as input and variables defining revenue and ridership as the output variables.

Results of the DEA analysis are summarised in Table 23. The DEA analysis revealed that paratransit services have a higher average technical efficiency of 85% i.e. they have the scope to reduce their inputs by 15% to produce the same outputs. Buses have a lesser efficiency of 72% implying that they can reduce up to 28% of their inputs for the same outputs. Buses also have a higher standard deviation indicating more inconsistencies in performance of various routes.

Table 22 Descriptive statistics of input and output variables for DEA

Name of variable	**Type of variable**	**Mode**	**Count**	**Average**	**Maximum**	**Minimum**	**Standard Deviation**
Vehicle Capacity (in passengers/ vehicle)	Input	Bus	92	56	60	45	7.06
		Paratransit	141	4.5	7	4	1.43
Daily mileage (in km)	Input	Bus	92	310	420	218	41.81
		Paratransit	141	92	300	10	49.02
Daily Income (in Indian Rupees)	Output	Bus	92	6952	11054	4070	1529.88
		Paratransit	141	350	1000	100	147.60
Daily Ridership (in passengers/ day)	Output	Bus	92	891	1947	323	329.39
		Paratransit	141	399	1305	43	213.27

Table 23 Efficiency of bus and paratransit services derived through DEA

Mode	Average Efficiency	Maximum Efficiency	Minimum Efficiency	Standard deviation
Bus	72%	100%	47%	13%
Paratransit	85%	100%	55%	10%

5.4 Review of operational planning practices of APSRTC

The comparision of operational characteristics and performance efficiency of bus and paratransit systems has shown that buses currently operate at a lower efficiency compared to paratransit. Even though the average bus occupancy of 59% fares well when compared with other global bus systems, when compared with average paratransit occupancy of 97% indicates the significant scope for improvements within the bus system too. Similarly, buses have 13% lower efficiency compared to paratransit, according to the DEA analysis. Therefore, the operational planning practices that led to the lower occupancy and efficiency of buses were reviewed to identify areas of improvement. A correlation analysis between key output indicators and input indicators maintained by APSRTC that best describe the existing bus operations was carried out for this purpose.

Ridership and revenue were considered as the key outputs of the bus system. The ridership achieved by the system was available in the form of Occupancy Ratio (OR), based on which the ridership numbers for the DEA analysis were derived. However, revenue data was available in greater detail i.e. in terms of the overall revenue generated from each route, average revenue generated per bus within a route and revenue per km of operations on each route. The route level OR and revenue performance act as aggregate performance measures of the system while the revenue per bus and revenue per km provide a further disaggregated performance measurement.

The input indicators were derived by matching the indicators suggested by (Jarboui et al., 2012) and (Daraio et al., 2016) with the data maintained by APSRTC. The four input indicators available to describe the existing bus operations are: length of each route, number of buses operating in each of the routes, the mileage of buses on various routes in terms of total vehicle km operated within each route and mileage of each bus in a route which together signify the level of activity of services provided in each route. Table 24 presents the results of the correlation analysis carried out between these indicators for the 92 city bus routes. The following is a brief interpretation of the results for each output indicator:

Table 24 Correlation analysis between input and output indicators of bus system

Output Indicator	Statistic	Input Indicator			
		Route length (in km)	Buses per route	Monthly veh-km per route	Daily veh-km per bus
Occupancy Ratio	Pearson correlation	0.063	0.067	0.087	0.147
	P-value	0.275	0.262	0.205	0.081
Revenue per route	Pearson correlation	0.046	0.946**	0.971**	0.252**
	P-value	0.333	0.000	0.000	0.008
Revenue per bus	Pearson correlation	0.296**	0.054	0.191*	0.668**
	P-value	0.002	0.304	0.034	0.000
Revenue per km	Pearson correlation	-0.047	0.040	0.021	-0.026
	P-value	0.328	0.354	0.419	0.404
Sample Size (N) = 92 routes for all indicators					
** Correlation is significant at the 0.01 level (1-tailed).					
* Correlation is significant at the 0.05 level (1-tailed).					

Occupancy ratio: It is observed that the route occupancy ratio is not significantly impacted by any of the input indicators concerning operations i.e. route length, buses allocated and their daily and monthly mileage.

Revenue per route: The three variable showing the total supply provided on a route i.e. number of buses available for each route, the overall veh-km operated in the route and the daily veh-km operated by each bus show significant correlation with the revenue generated in a route. Increased supply leading to increased revenue indicates the availability of latent demand for bus services. At the same time, the length of the route isn't significantly correlated with its revenue.

Revenue per bus: Correlation analysis of revenue for each bus within a route is positively correlated with the length of the route on which it operates along with the monthly and daily veh-km operated. However, it isn't correlated with the number of buses deployed on the route possibly indicating that the revenue of each bus is a function of its own supply performance and isn't dependant on the total bus supply on the route. This again indicates that there's adequate latent demand to travel on buses if they provide more services

Revenue per km: It is observed that this indicator does not show significant correlation with any of the input indicators considered.

The analysis generated interesting insights on the revenue performance of buses in relation to various inputs. The results for revenue per route and revenue per bus indicate the availability of latent demand willing to use buses if they can provide more service. At the same time a more disaggregated analysis to analyse revenue per km of service shows that it isn't correlated with any of the supply indicators suggesting that the net increase in revenue for every km of service can't just be explained by internal efficiency metrics and will require further analysis to understand external factors impacting bus ridership and revenue.

However, all the indicators currently maintained by APSRTC concern the operations of the bus system. None of the indicators concerning travel demand characteristics i.e. trip length, travel time, hourly demand variation etc. are measured. The lack of correlation of the two output indicators measuring operational efficiency in terms of the occupancy ratio and revenue per km lead to the conclusion that input indicators just measuring operational characteristics are inadequate to explain operational performance. The operators need to include indicators measuring travel demand characteristics and user perception towards public transport to plan their operations accordingly and thereby attract higher ridership and revenues.

5.5 Summary of findings from user and operator characteristics analysis

The comparision of user characteristics revealed that most of the socio-economic and travel characteristics of city bus and paratransit users are significantly different. Such differences indicate that the two modes cater to separate sets of public transport users within the city. Users' choice between the two modes was chiefly influenced by their journey time resulting in a preference for the low-occupancy and high frequency paratransit services for shorter trips and buses for longer trips, where wait time constitutes a smaller proportions of the trip.

Analysis of the operational characteristics of the two modes revealed that they perform varying roles in catering to the city's travel needs. The city bus system operates with a service motive i.e. to maximise access to mobility for the citizens while paratransit operates with a profit motive only on high demand corridors and during peak hours. The bus system provides assured service for 16 hours every day, has a network reach throughout the city and carries three times more passengers than the paratransit system. However, the bus system also has is 13% lower operational efficiency which can be partly attributed to operating in non-peak hours and their wider network. Another key reason for the lower efficiency of buses is that the current operational plans of the bus system only monitor the historical performance of various routes and do not consider the ever-changing user demand requirements in the city.

On the other hand, the small vehicle size of paratransit enables them to have high percentage occupancy and their large numbers enable high frequency services. By being dynamic and demand responsive, paratransit performs a key role in augmenting services in corridors with insufficient public transport supply. Therefore, the bus system needs to update their operational planning and data maintenance practices to consider user demand and perception related attributes in addition to the physical performance attributes, to make their services demand responsive thereby improving their occupancy and revenue efficiency.

The findings from the analysis of both users' and operators' characteristics, indicate the varying roles of bus and paratransit systems. Therefore, the city should move towards an integrated planning and operations optimisation framework that incorporates users travel demand preferences for bus and paratransit services and provides assured bus services which are complemented by the flexibility and demand responsiveness of paratransit. Such a system will improve the overall level of service of public transport in cities.

6 Transit assignment and frequency optimisation for Visakhapatnam

The travel demand, road network and operational characteristics data presented in Chapter 5 is used to carry out the transit assignment and frequency optimisation analyses. Transit assignment is carried out using TransCAD (academic version 6.0), a transportation Geographic Information Systems (GIS) software while frequency optimisation was carried out using CPLEX Optimisation Studio (academic version 12.7.1), an operations research tool with efficiency optimisation modelling and solving capabilities. The overall travel demand model of the city, transit assignment and frequency optimisation stages are explained in separate sections below.

6.1 Developing the travel demand model for Visakhapatnam

The four stage travel demand modelling methodology proposed by Ortuzar and Willumsen (2014) is adopted for developing the travel demand model for the current thesis. Figure 16 Figure 16 Methodology for developing the Travel Demand Model of Visakhapatnampresents an overview of the methodology. TransCAD 6.0, a GIS based travel demand model is developed to replicate the road network and travel patterns of the city and to test various travel demand and transit supply scenarios. Table 25 summarises the data sources for various input parameters required for the model. Various stages of the modelling procedure have been explained in the following sections.

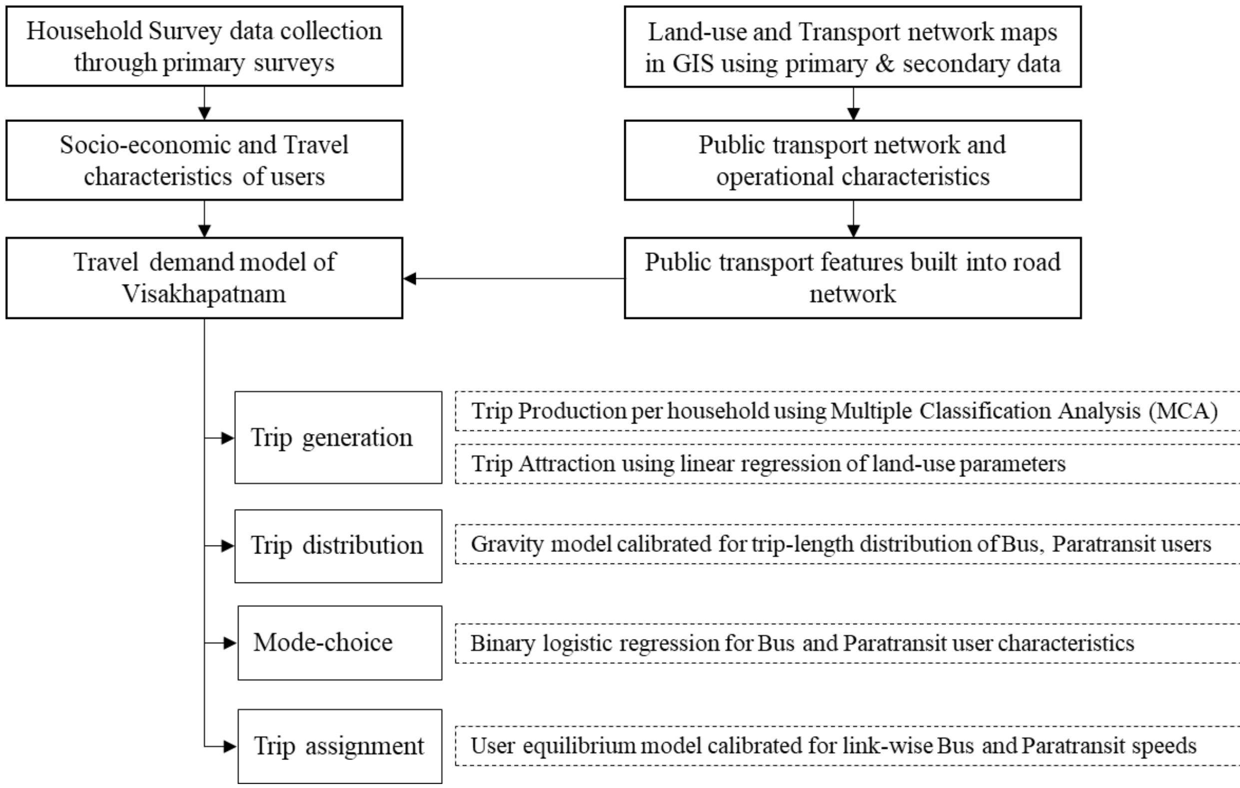


Figure 16 Methodology for developing the Travel Demand Model of Visakhapatnam

Table 25 Modelling components and input sources

Model Component	**Input Source**
Traffic Analysis Zone Map	Derived from Ward Map
Road Network	Derived from Property Tax Data, Primary Data collected for road inventory & Link speeds and secondary data on road widths
Trip Production Patterns	Household Interview Data
Trip Attraction Patterns	Land Use Data from Master Plan and Building wise usage type from Property Tax Database

Trip Distribution	Trip length distribution patterns from Household Interview data to calibrate the Gravity Model
Base Mode Shares	Household Interview Data
Traffic Assignment	Traffic Volume Counts used for network calibration

6.1.1 Traffic Analysis Zones and Road Network Building

Traffic Analysis Zones (TAZ) and the road network are the basic building blocks of the travel demand model. TAZ are the units of disaggregation for trip productions and attractions from various parts of the city. TAZs are identified in such a way that the land use type and trip making characteristics of all developments in a particular TAZ are assumed to be homogeneous. Trips between various TAZs are made using the road network of the city. Hence the road network attributes like the likely travel time and capacity of each link are required to replicate the actual network of the city.

TAZs and road network for the municipal limits of Visakhapatnam developed for (iTrans, 2014a) were used as the input for this thesis. The 72 municipal wards of Visakhapatnam were divided into 97 zones, with each zone having homogeneous land use pattern and an average area of approximately 1 sq.km. The area, population and land use data of each zone was included in its attribute table. The road network including the attributes corresponding to the public transport network, as explained in section 4.4 is used for analysis. The TAZ map and road network used for the travel demand model are presented in Figure 17. While the travel demand model included the entire road network of 625 kms, only 212 km i.e. 34% of the road network has access to the combined public transport network in the city comprising of the bus and paratransit system. Within the public transport network 89 km of roads have access to both bus and paratransit systems, while

120.6 km have access to just the Bus system. Only 2.3 km of the public transport network has exclusive access to the paratransit system. Various network attributes required for modelling like the link speed, travel time, road widths, effective capacity, availability of public transport were built for the above network based on various primary and secondary data sources. This network, represented in Figure 18, is used for further four-stage modelling.

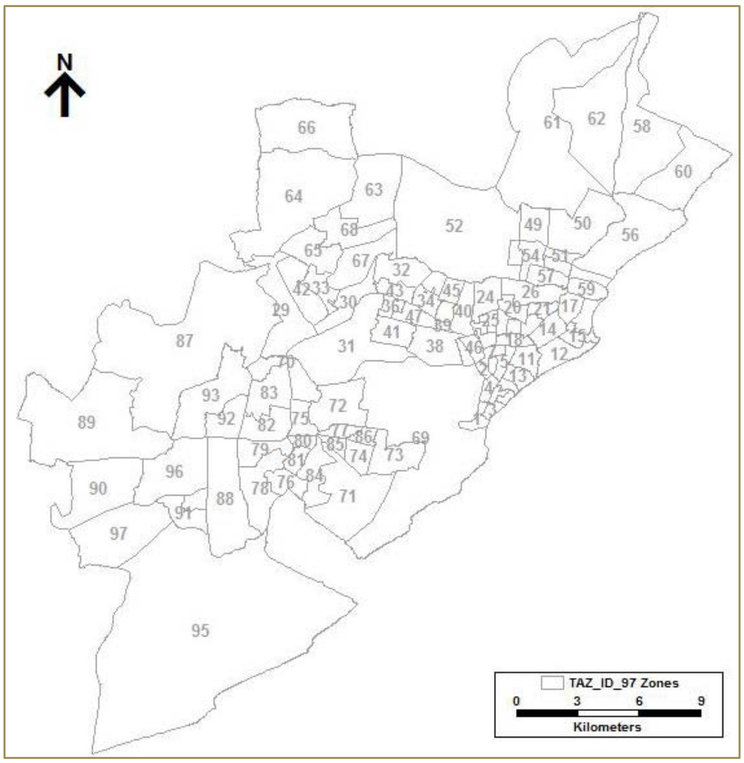


Figure 17 Traffic Analysis Zone (TAZ) map of Visakhapatnam showing the 97 zones

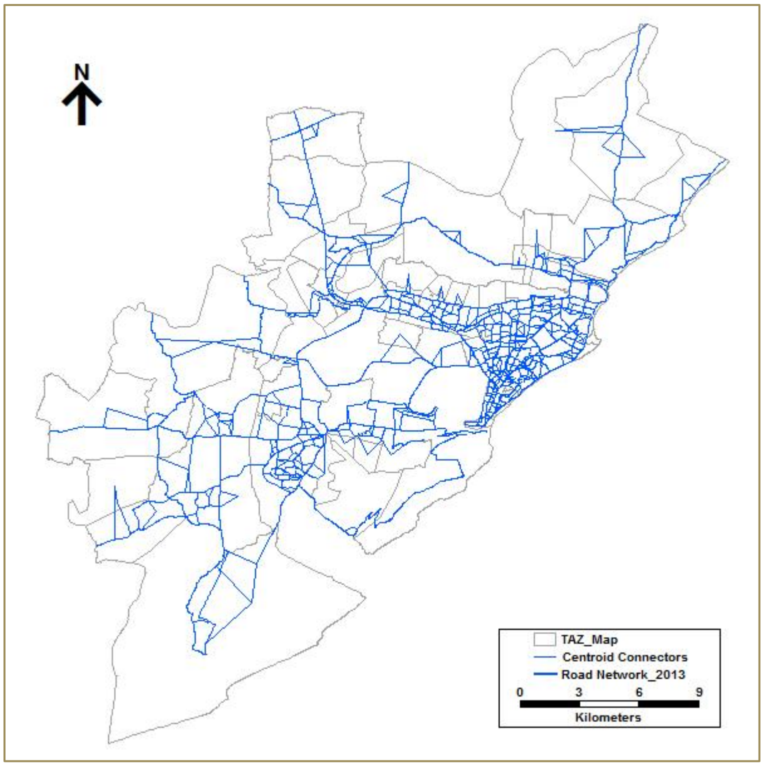


Figure 18 Road network used for modelling (including connectors)

6.1.2 Trip Generation

The trip generation stage of the model involves estimating the number of trips produced and attracted to each TAZ. Trip production is commonly estimated based on socio-economic characteristics of households within the TAZ while trip attraction depends on its land-use type (Gadepalli et al., 2014b, Guevara and Thomas, 2007, Gymmy Joseph Kattor, 2013). Household interview data collected for Visakhapatnam was used to estimate the trip productions in each TAZ based on the various types of households and their socio-economic characteristics. This was done for the trip production data of the 3,021 sample of households interviewed. The following steps are followed to estimate the total trips produced in each TAZ:

i) The socio-economic characteristics of each TAZ were derived from the household interview data

ii) Relation between purpose wise trips produced in each household and the socio-economic characteristics of the household are observed for the entire data collected.

iii) Multi-variable cross-classification method is used for trip production estimation

iv) Total number of households in each TAZ are derived from the property tax database of Visakhapatnam

v) Based on the socio-economic characteristics of the TAZ and the total households, total number of trips produced in each TAZ are estimated.

Trip production using Multi-variable Cross-classification Analysis (MCA)

Cross-classification analysis is used to identify the trip rates of various households for a combination of variables that influence trip rates. This modeling procedure leads to greater disaggregation than any other trip production models (Guevara and Thomas, 2007, Meng et al., 2009, Gadepalli et al., 2014a). An MCA table shows the number of daily trips produced per household whose characteristics are stratified by a combination of household attributes which are most appropriate to describe trip productions. The variables are categorized such that the households are divided into a limited set of combinations. The variables identified from the literature that were tested for Visakhapatnam are explained below:

- **Household size**: This is the most influential variable for trip production. Based on the frequency distribution, household(HH)s are categorized into HH sizes <=2, 3,4, 5, >=6 i.e. HHs with size1 or 2 are clubbed into one category and all HHs with size >=6 are clubbed into a single category
- **Household Income** is the second variable that is observed to affect the trip rates of a household, since richer households are likely to make more recreational trips. Even though

income data is collected in the HH Interviews estimating income based on the assets owned by a household is considered to be a more robust way of estimating income. Based on their assets total households have been divided into three categories in increasing order of income:

- **Inc. Category 1-** Low income households: Living in temporary settlements or living in tiled roof buildings without the assets mentioned above
- **Inc. Category 2-** Medium income households: Living in semi-permanent tiled roof households and masonry structures owning either a two-wheeler/ motorcycle or a refrigerator or an AC. Households living in concrete structure but without the assets mentioned above were also categorised as medium income groups
- **Inc. Category 3-** High income households: Living in multi-storeyed apartments or concrete structures and owning either at least a Car or the combination of a two-wheeler/ motorcycle and an Air-Conditioner (AC)

- **Motorised vehicle ownership**: The share of cycle based trips in Visakhapatnam was only 3% of the total trips. Therefore, motorised vehicle ownership i.e. cars and two-wheelers were observed to be having a larger influence on trip production. Therefore two categories of motorised vehicle ownership were considered for the cross classification analysis i.e. HHs owning no motorised vehicles and HHs owning at least one motorised vehicle i.e. either a Car or a 2-wheeler. However vehicle ownership can be a dependent on the income of the household

Various combinations of these variables are considered for various trip purposes and the trip rate trends observed are shown in Figure 19, Figure 20 and Figure 21.

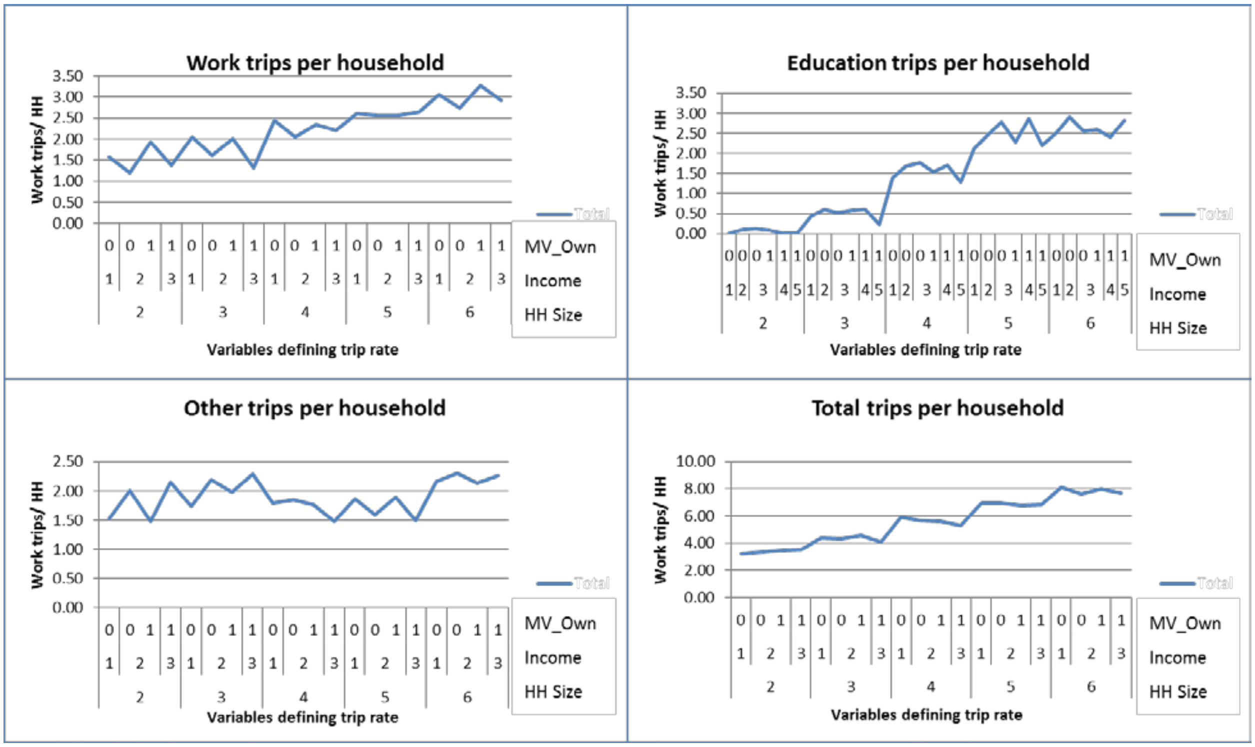


Figure 19 Cross-Classification Trip rate charts for combination of three variables

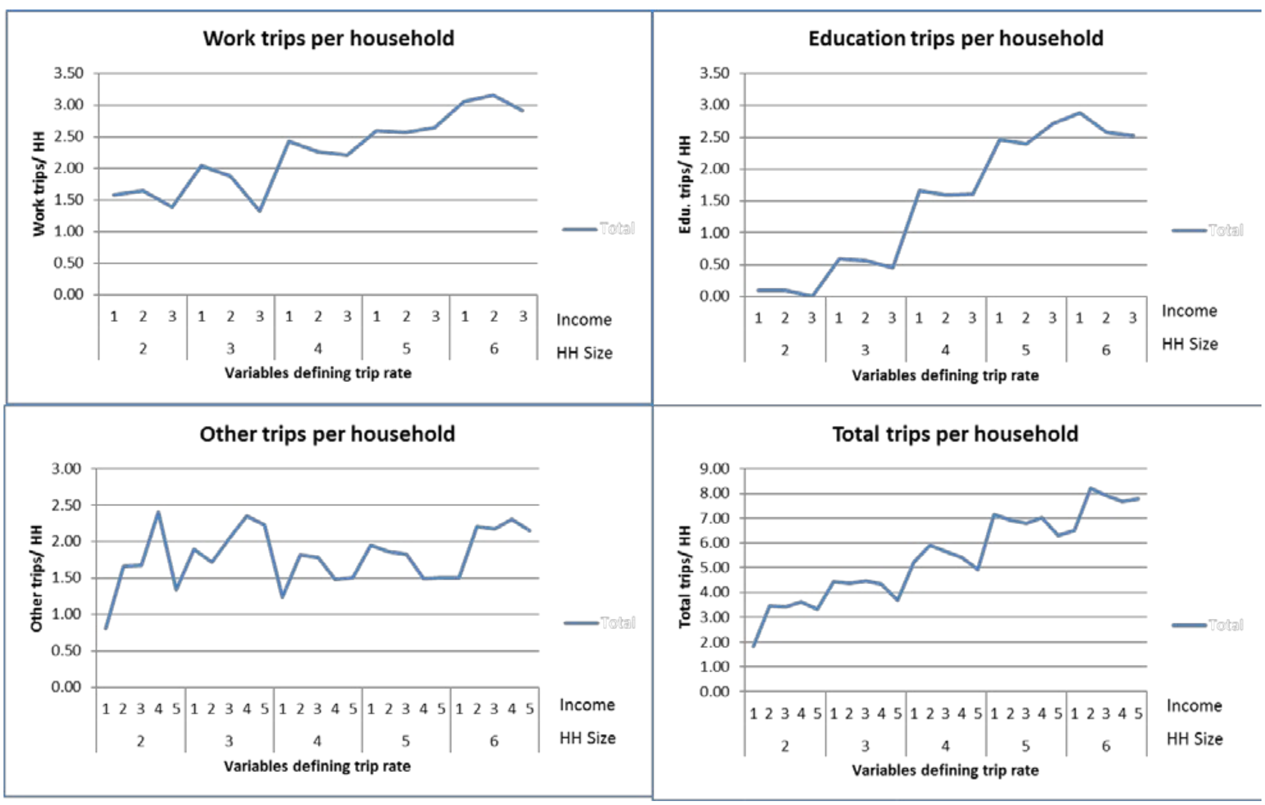


Figure 20 Cross-Classification Trip rate charts for combination of two variables

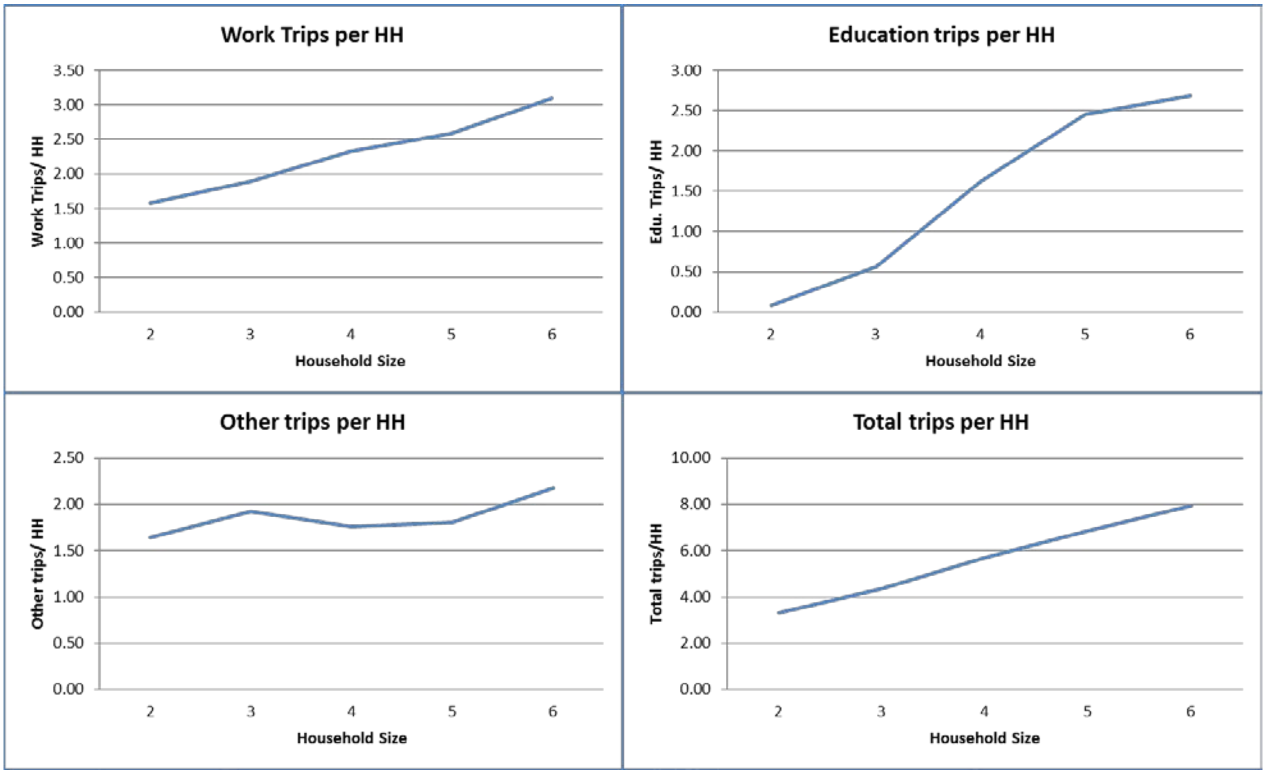


Figure 21 Cross-Classification Trip rate charts for combination of one variable

The cross-classification analysis for two and three variables did not show any clear trend in trip rates. Therefore, HH Size was identified as the only variable having significant influence on trip rates. Therefore this variable was used to estimate the trips produced in each TAZ based on the average HH Size observed in the TAZ. Table 26 presents the trip rates adopted for various Household sizes.

Table 26 Trip rate table used for Trip Production

HH Size	Work Trips/HH	Education Trips/ HH	Other Trips/HH	Total Trips/ HH
<=2	1.58	0.09	1.64	3.31
3	1.89	0.57	1.93	4.39

4	2.33	1.63	1.76	5.71
5	2.59	2.46	1.81	6.85
>=6	3.09	2.68	2.18	7.95
Average	**2.53**	**1.97**	**1.91**	**6.41**

The total number of households in each TAZ was derived by extrapolating the trip rates derived for the sample households in each TAZ to its total number of households by overlaying the property tax GIS layer with the TAZ layer. It was already presented in Table 11 that the Household (HH) size of each TAZ derived from the survey was representative of the actual HH Size of the city. Therefore, the trip rate is derived from its average HH Size and the total trips produced are derived by multiplying trip rate with the number of households

Trip Attraction using land use characteristics

Trip attractions to each TAZ were estimated based on the attractiveness of a zone measured as a function of its land-use type. For example residential land uses produce trips while commercial, institutional and industrial areas typically attract trips (Ortúzar and Willumsen, 2011, Gymmy Joseph Kattor, 2013, Pretina George, 2013). Hence the existing land use mix is considered as the critical variable in determining the trips attracted to each TAZ. Land use data at the city level is provided by the Master plan of the city, but they are only indicative as the land use allocation in the master plan and the actual usage of land use is observed to be varying widely in practice (VUDA, 2007).

The property tax data of Visakhapatnam has building wise land use type and its plinth area. Types of land use in the buildings include: Residential, Commercial, Educational, Industrial, Public Use, Shops, Hospital, Cinema/Pub Entertainment, Others. Except residential, all other land use types attract trips. Hence, the total plinth area of each type of attracting land uses is calculated and is used as a measure of attractiveness of the TAZ. Figure 22 shows the spread of buildings of various land use types across the city.

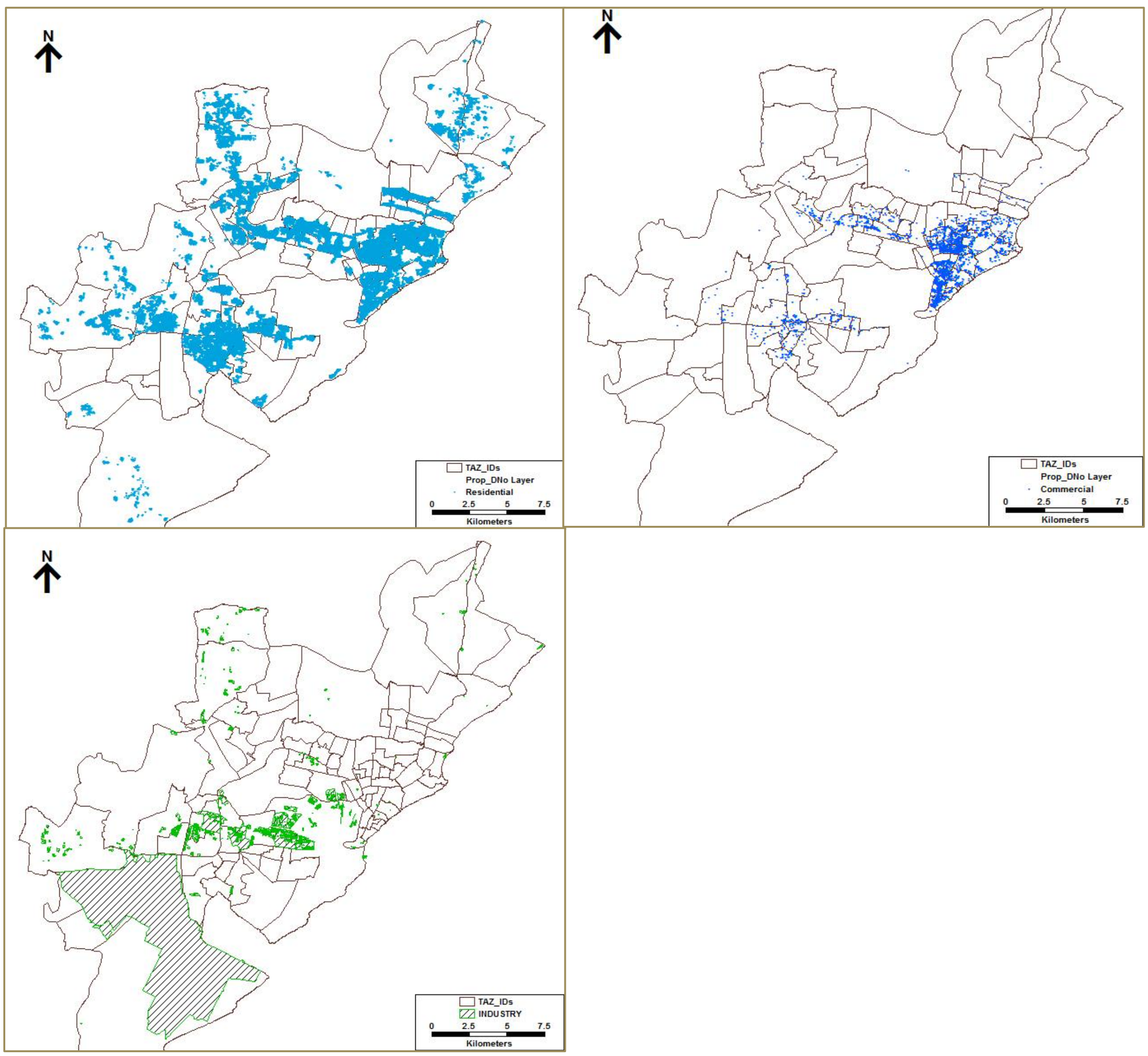


Figure 22 Distribution of residential, commercial and industrial landuse patterns in Visakhapatnam

Multi-linear regression is the most used method in literature to estimate trip attraction rates. Washington and Wolf (1997) compared linear regression models with hierarchical tree-based models to conclude that results from a regression based approach are easier to interpret compared to hierarchical models where omitted variables and outliers are harder to deal with. (Zenina and Borisov, 2013) also present the validity of regression models in explaining trip production and attraction behaviour. Applicability of regression models to predict trip attraction behaviour for various contexts and input data sets are also presented in literature (Badoe and Chen, 2004, Itoh and HATO, 2013, Zin et al., 2018).

Therefore, the current study adopted a land-use type based prediction for trip attractions using multi-linear regression. Purpose wise trips attracted to each zone from the household interviews is used as the dependent variable and the total plinth area of land use types are used as the independent variables and multiple linear regression is used to observed the relation between the trips attracted, derived from the sample trips from household survey and the land uses of the TAZ. The regression equations derived for each trip purpose trips as a function of land use are given below. Equation 15 provides the equation derived for work trips and the corresponding regression statistics are presented in Table 27. Equation 16 provides the equation for education trips, with the regression statistics presented in Table 28. The other trips' regression is presented in Equation 17 while Table 29 presents its regression statistics.

- **Work Attraction**:

$$\mathbf{Work_{Attr} = 15.97 + 0.003*Commercial + 0.005*Industrial} \qquad \mathbf{15}$$

(Coefficient of Determination (R^2) = 0.55, Standard error = 67.18)

Table 27 Regression Statistics for Work Attraction

Dependent variables (land use categories)	Unstandardized Coefficients		Standardized Coefficients	t-value	$t_{critical}$	Sig.
	B	Std. Error	Beta			
(Constant)	15.973	10.474		1.525	1.96	0.134
Commercial	0.003	0.000	0.435	5.635	1.96	0.000
Industrial	0.005	0.001	0.564	7.300	1.96	0.000

Education Attraction:

$$\mathbf{Edu_{Attr}=-0.628+0.005*\ Commercial\ +0.001*Educational} \quad \mathbf{16}$$

(Coefficient of Determination (R^2) = 0.98, Standard error = 65.34)

Table 28 Regression Statistics for Education Attraction

Dependent variables (land use categories)	Unstandardized Coefficients		Standardized Coefficients	t-value	$t_{critical}$	Sig.
	B	Std. Error	Beta			
(Constant)	-0.628	8.216		-0.076	1.96	0.939
Commercial	0.005	0.000	0.982	41.809	1.96	0.000
Educational	0.001	0.000	0.055	0.976	1.96	0.357

Other Trips Attraction:

$$\mathbf{Oth_{Attr}=31.882+0.001*\ Commercial} \quad \mathbf{17}$$

(Coefficient of Determination (R^2) = 0.35, Standard error = 32.94)

Table 29 Regression Statistics for Other trips attraction

Dependent variables (land use categories)	Unstandardized Coefficients		Standardized Coefficients	t-value	$t_{critical}$	Sig.
	B	Std. Error	Beta			
(Constant)	31.882	4.605		6.923	1.96	0.000
Commercial	0.001	0.000	0.350	2.989	1.96	0.004

The number of trips attracted to each zone was calculated using the equations. However, this only derived the number of trips at the scale of the sample size of data and hence these attractions were used as the relative attractiveness of each zone. The total attractions to each zone were estimated using 'Production-Attraction (PA)' balancing technique available in TransCAD. It proportionally scales up attractions in each zone in proportion to their attractiveness, such that the total attractions of all the zones are equal to the total trips produced across all the zones, segregated by trip purpose.

Peak hour trip productions and attractions

The productions and attractions presented above give the daily trip generation patterns across trip purpose categories. The transit assignment and frequency optimisation for the current thesis were carried out for the peak hour to determine the maximum fleet requirement in the city. Therefore, the travel demand model was carried out for peak hour demand. Therefore, the household survey data was used to derive hourly variation of trip making behavior across trip purposes. Table 30 shows the hourly variation of various trip purposes, derived from the household surveys. 8:00 AM to 9:00 AM was identified as the peak hour for the city across trip purposes. This was also validated by observations from the traffic volume count surveys carried out for the LCMP and hence this is taken as the peak hour for the demand model. Therefore, the trip productions and attractions were derived based on the hourly variation of the trips of each purpose.

Table 30 Hourly variation of trips for each purpose

Time of Day		Trip Purpose			
From	**To**	**Work**	**Education**	**Others**	**Average**
4:00	5:00	1%	1%	0%	1%
5:00	6:00	2%	3%	1%	2%
6:00	7:00	4%	4%	3%	6%
7:00	8:00	5%	11%	10%	8%
8:00	9:00	**19%**	**30%**	**25%**	**22%**
9:00	10:00	16%	12%	10%	12%
10:00	11:00	6%	3%	3%	6%
11:00	12:00	2%	1%	2%	3%
12:00	13:00	2%	1%	0%	2%
13:00	14:00	2%	1%	2%	2%
14:00	15:00	3%	2%	1%	2%
15:00	16:00	2%	2%	3%	2%
16:00	17:00	9%	11%	9%	9%
17:00	18:00	10%	9%	15%	9%
18:00	19:00	8%	5%	4%	6%
19:00	20:00	4%	3%	3%	3%
20:00	21:00	3%	1%	5%	2%
21:00	22:00	2%	1%	1%	2%

22:00	23:00	1%	0%	1%	1%
Grand Total		100%	100%	100%	100%

Source: (iTrans, 2014a)

6.1.3 Mode split of trips

The purpose wise trips derived from the peak hour were later aggregated to derive the total trips made during the peak hour. This was further disaggregated into mode wise trips based on the modal shares reported in each TAZ during the household surveys. One of the features of the four-stage demand modelling process is that a TAZ is represented by its centroid i.e. an imaginary point of origin and destination of all trips starting or ending in a ward. As a result, the model considers all trips made within a zone as zero and models only the inter-zonal trips. Hence, the proportion of intra-zonal trips in each TAZ are calculated from the HH Interview data and these trips are excluded from the demand modelling process. While this showed a significant impact on walk and bicycle trips, the impact on bus and paratransit modelling was negligible since most of them were inter-zonal trips.

6.1.4 Trip distribution

The mode-wise trip productions and attractions of each TAZ were used as the input for trip distribution. Trip distribution is used to derive the Origin-Destination (OD) matrix for each mode from the PA table. Gravity Method is applied for trip distribution using the following steps:

Gravity Application

- Gravity application derives OD matrices with the assumption that number of origins and destinations between wards is directly proportional to the productions in the originating TAZ and attracting TAZ and inversely proportional to the impedance between these zones.

Impedance is a measure of the disincentive to travel between two wards. For eg. travel time, trip length, cost of trip etc.

- The speed and travel time for each link were defined separately for each mode. These speeds are based on the mode-wise speeds observed on various links, from the speed-delay survey
- In this step, Production-Attraction (PA) tables of each mode were considered separately and the Gravity method is applied for each of them
- Travel times between TAZs was used as the key impedance for users and therefore skims i.e. matrixes with congested travel times between various TAZs were generated for each mode according to their speeds. The congested travel times were derived from LCMP.
- Using the PA table and travel time skim for each mode, separate OD matrices are derived for each mode

Gravity Calibration

- The above gravity application considered inverse power function as the distribution for the impedance function using its default parameters

$$f(c_{ij}) = c_{ij}^{\alpha}$$

- However, the trip time distribution of various modes varies and hence the distribution from gravity application were calibrated based on mode-wise distributions from the household survey data
- The parameters of the inverse-power function are calibrated in such a way that the gravity application output matches with the actual trip time distribution

Table 31 shows the table including calibrated values of the inverse power function for various modes. Using these updated values for the inverse power function and the mode-wise PA tables and travel time skims, the calibrated OD matrix for each mode is derived.

Table 31 Calibrated values for Trip distribution Impedance

Mode	Default α	Calibrated α	Root Mean Square Error (RMSE)
Car	-0.45	-0.420	7.50%
Two-wheeler	-0.45	-0.460	5.90%
Bus	-0.45	-0.350	2.70%
Paratransit (Three-wheeler)	-0.45	-0.470	1.40%
Bicycle	-0.45	-0.520	13.70%

6.1.5 Traffic Assignment

The Trip distribution output gives the OD matrix of person trips originating within the city. These person trips were converted to vehicle trips based on the average occupancy observed in each mode from the occupancy survey carried out in the city, as presented in Table 32. Traffic assignment will require two key inputs:

i) Network: Initially trips of all modes were assigned to road network.

ii) Travel demand: The total travel demand including Origin Destination (OD) matrices across all modes

Table 32 Mode-Wise Average Occupancy

Mode	Average Occupancy
Car	2.5
2-Wheeler	1.5
Bus	30
Paratransit	4.9
Cycle	1

Source: Occupancy Surveys, LCMP Visakhapatnam (iTrans, 2014a)

The trip generation and OD matrices derived until now were from ODs mentioned in the household surveys i.e. for home bound trips. However, cities also have many trips which do not originate from households i.e. trips entering the city through inter-city travel, between commercial areas and other work, recreational trips etc. Therefore, OD surveys were conducted at various key locations in the city and the sample data from these surveys were scaled up based on the traffic volume counts at those locations. Figure 24 shows the 19 locations of traffic volume counts in the city to measure the actual traffic volume at various locations. More locations are covered in the core area than outskirts due to the heavy traffic observed there.

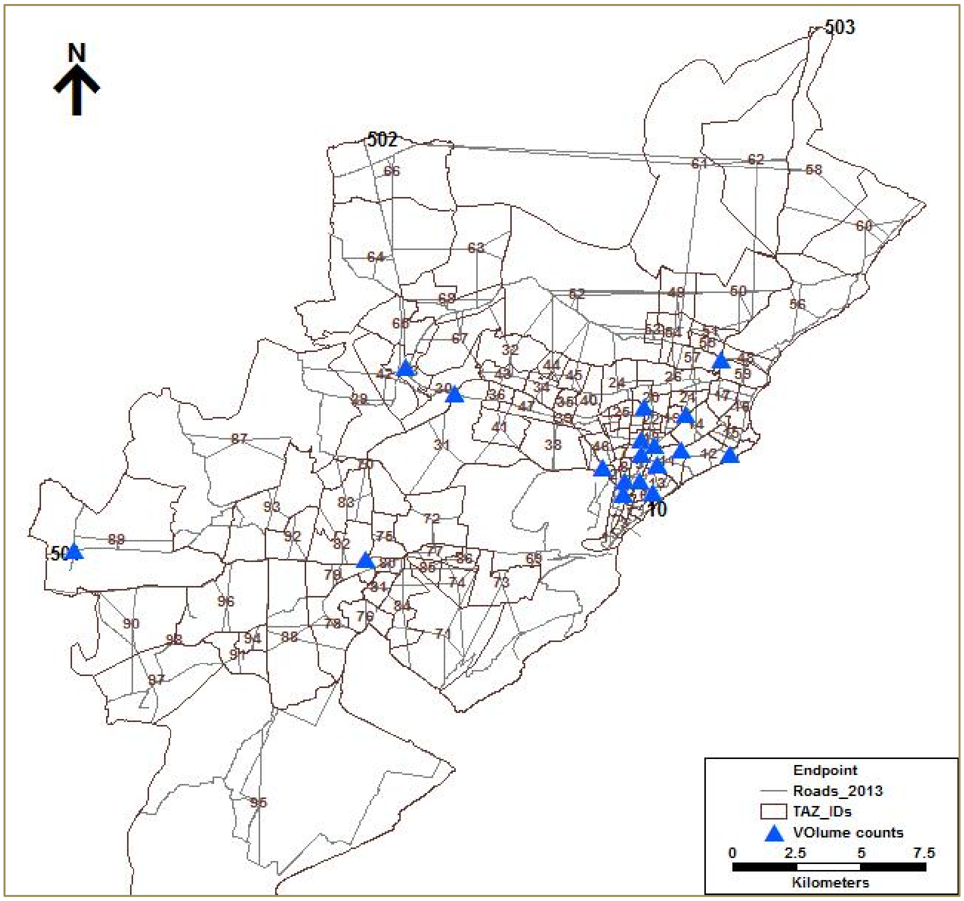


Figure 23 Volume Count locations for OD matrix estimation

The OD matrices from these surveys are added to the OD from trip distribution to develop the overall OD matrix of the city. The mode-wise calibrated OD matrices derived from the above step are assigned on to the road network using User Equilibrium method in TransCAD which assumes that each user selects the route that gives the shortest travel time to him. The travel time used is the congested ravel time calculated as a function of free flow travel time on the link, its capacity and traffic demand. The Bureau of Public Roads (BPR) function was used to define the volume-delay function:

$$t_i \cdot \left[1 + \alpha_i \left(\frac{x_i}{C_i} \right)^{\beta_i} \right]$$

where:

t_i = Free flow travel time on link i

C_i = Capacity of link i

x_i = Flow on link i

α = Constant

β = Constant

Default values of the software for α and β i.e. 0.15 and 4 are used for the model. These α and β values were continued as default, since the network has already taken congestion travel time in the previous stages i.e. the impedance matrix. Since the travel time skim matrix is already taking mode-wise speeds based on survey data, the BPR function has not been changed from default parameters.

OD matrix estimation

The link flows observed from traffic assignment are compared with the actual traffic flows observed from traffic volume counts conducted at 20 intersections across the city. This translates to 76 mid-blocks, considering each intersection has 3/4/5 arms. It was observed that the link flows from traffic assignment varied from the traffic volume counts. Some missing links in the road network are identified through this procedure. However, the larger contributing factor to this error is the OD matrix derived from trip distribution. OD matrix had to be re-calibrated for it to match the traffic volume counts. For this, an iterative process available in TransCAD called, the OD matrix estimation is used.

OD matrix estimation procedure considers the observed traffic volume counts and updates the OD matrix based on them. It takes each location separately and updates the OD matrix iteratively until the assignment from the revised/ calibrate OD matrix matches the traffic volume counts at all locations, within a permissible degree of error. Using this method, the final calibrated OD matrix and the calibrated traffic flows at all locations of the city are derived. Figure 25 gives the details of the iterative accuracy achieved through OD Matrix estimation. The calibrated network flows after OD matrix estimation are shown in Figure 25.

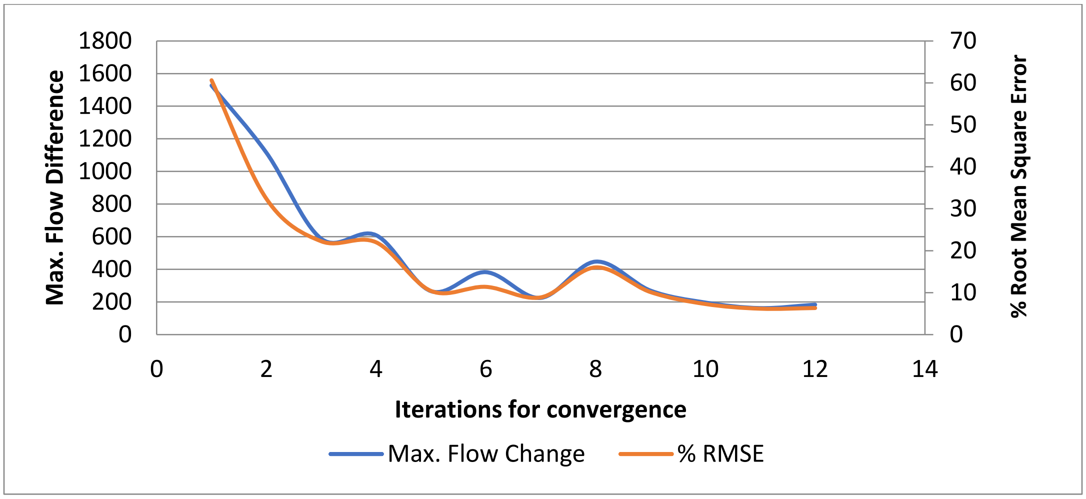


Figure 24 OD matrix estimation for traffic assignment model performance

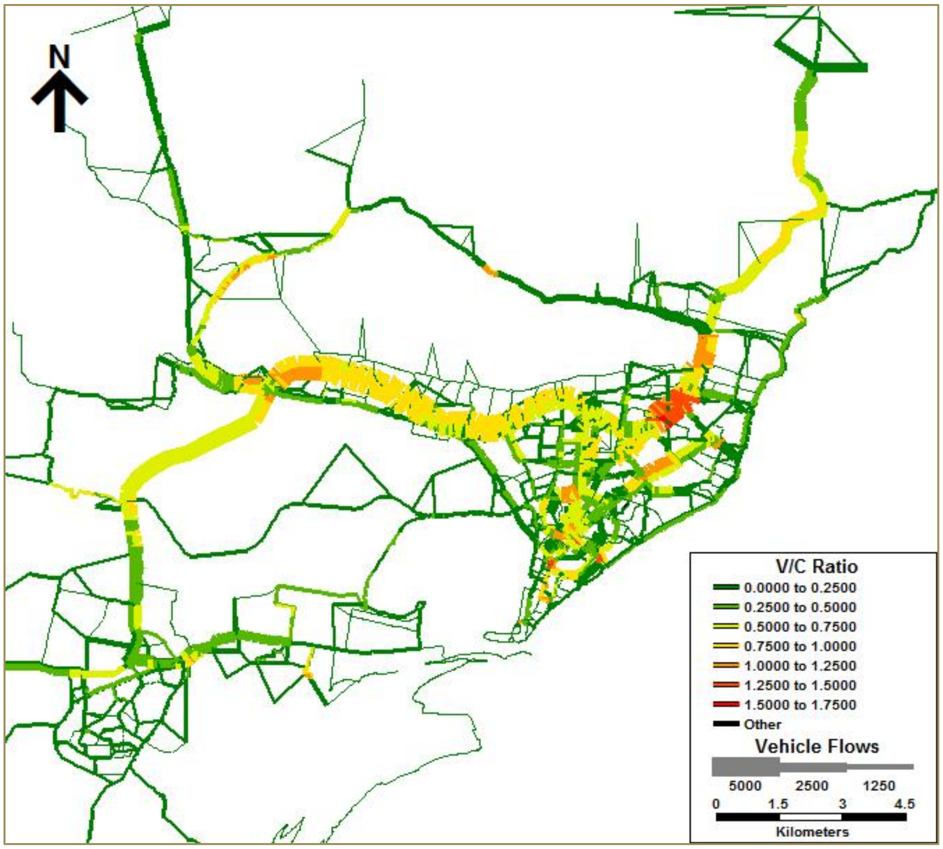


Figure 25 Output of traffic assignment in TransCAD

With this step the base year travel demand model is calibrated and can be used for further analysis.

The following table gives the key statistics for the calibrated model.

6.1.6 Key statistics from the travel demand model

In summary, the following are the key statistics for the calibrated base year model:

Population of the city, 2011 : 17,30,328

Total City Area : 534 sq. km.

Built-up area : 166 sq. km.

Average Household size : 4.0

Average trip rate : 6.41 trips/HH

Peak hour : 8-9 AM

Peak Hour Factor (person trips) : 22%

Total road length : 3,470 km

Length of Arterial+ Sub-arterials : 430 km

Mode wise statistics are shown in Table 33.

Table 33 Mode-wise summary of base year model

Mode wise details	Mode Share (%)	Trips/mode	Average trip length (in km)	Vehicle kms –Peak hour
Car	2	55,716	9.6	5,34,876
2-Wheeler	15	4,17,872	5.7	23,81,872
Bus	18	5,01,447	10.5	52,65,190
3-Wheeler	9	250,723	5.0	12,53,617
Walk	52	14,76,482	0.7	10,33,537
Cycle	3	83,574	3.1	2,59,081
Total for the city	100	27,85,815	4.0	1,11,43,260

6.2 Transit Assignment

The travel demand model, including traffic assignment and OD matrix estimation presented in section 6.1 was carried out to develop the entire travel demand model for Visakhapatnam. This model was calibrated using the traffic volume counts carried out at various locations in the city. This model was used as the base to develop the transit assignment model required for frequency optimisation. Separate assignment and calibration was carried out for bus, paratransit and the combined transit scenarios so that the passenger flow outputs can be used as input to frequency optimisation such that their results can be compared across separate and combined assignment scenarios. Figure 26 and Table 34 present a summary of network and travel demand characteristics which were used as the input to the model.

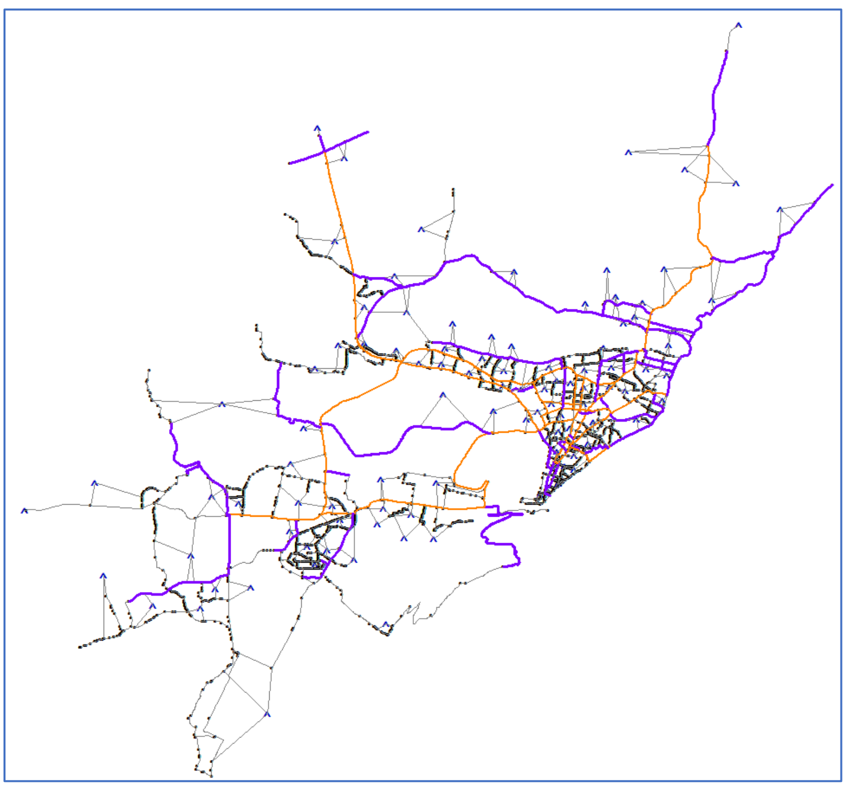


Figure 26 Road network of Visakhapatnam with access to bus and paratransit services

Table 34 Transit demand inputs to Visakhapatnam travel demand model

Parameter	Bus	Paratransit	Total
Population of the City			17,30,320
Modal share of public transport	18%	9%	27%
Average trip length (in km)	10.81	5.62	9.05
Per-Capita Trip Rate (PCTR)	0.29	0.14	1.61
Passenger Car Units (PCU)*	3	1	
Particulate matter (PM 2.5) emission factor	0.506	0.109	
Total daily trips	4,98,049	2,64,444	27,85,815
Peak hour trips (8-9 AM)	1,33,192	81,961	2,15,153
Excusive network length for each mode(in km)	120.6	2.3	
Network length with both Bus and paratransit (in km)	89		
Total network length (in km)	209.6	91.3	211.9
Total city road network length (in km)			624.6

*Source:(IRC, 1994a)

6.2.1 Transit assignment and network calibration

The following steps were followed to carry out the transit assignment for public transport i.e. bus and paratransit services in Visakhapatnam:

- The calibrated road network from the travel demand model was considered as the input
- The 212 km out of the 624 km of road network which has access to either bus or paratransit users were marked as public transport network, while the rest of the network is marked as access and egress links to the system
- Including separate bus and paratransit network attributes was needed because some links have access to only of the two systems therefore making those access and egress links to the other

system. For eg. Within the public transport network, if a certain link only has bus routes passing through it, it will have capacity and travel time attributes according to bus system for bus assignment, as access and egress links for paratransit assignment and public transport attributes for the combined transit assignment

- The link speeds and travel times were derived from the secondary data available from LCMP, Visakhapatnam. The capacity of the bus system on its network was derived using secondary data from APSRTC, the bus operator while the paratransit capacity was derived based on LCMP data using the maximum observed paratransit traffic volumes along various corridors
- Within the public transport network, bus links, paratransit links and links that have both bus and paratransit were added to the road network were identified. Their network attributes like availability of bus and paratransit on the link, capacity, speed and travel time for either or both modes have been adopted accordingly
- Separate bus, paratransit and total transit travel time matrices were derived based on their network attributes
- Bus, paratransit and total transit assignments were carried out using user equilibrium method. Their travel time matrices were used as the impedances for network assignment. Travel cost isn't taken within the impedance function as it wasn't a significant variable in the binary logit model
- The OD Matrix Estimation (ODME) procedure explained in section 6.1 was applied to calibrate the bus, paratransit and total transit network attributes separately. These networks were calibrated in 168, 178 and 136 iterations respectively, the summary of which is presented in Figure 27 to Figure 29.

The outputs of the calibrated network's transit assignments were link wise transit flows for bus, paratransit and total transit demands. These flows were used as the input for frequency optimisation.

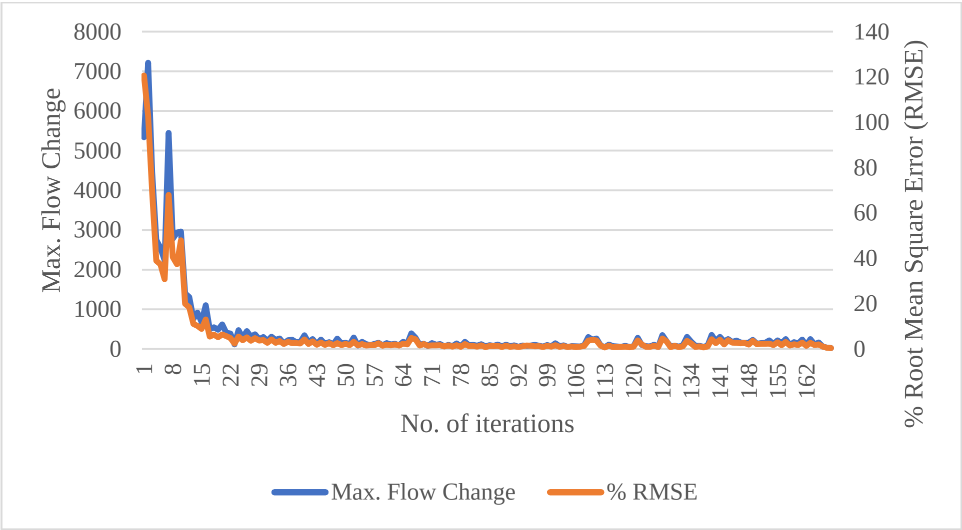


Figure 27 Model performance for bus network calibration

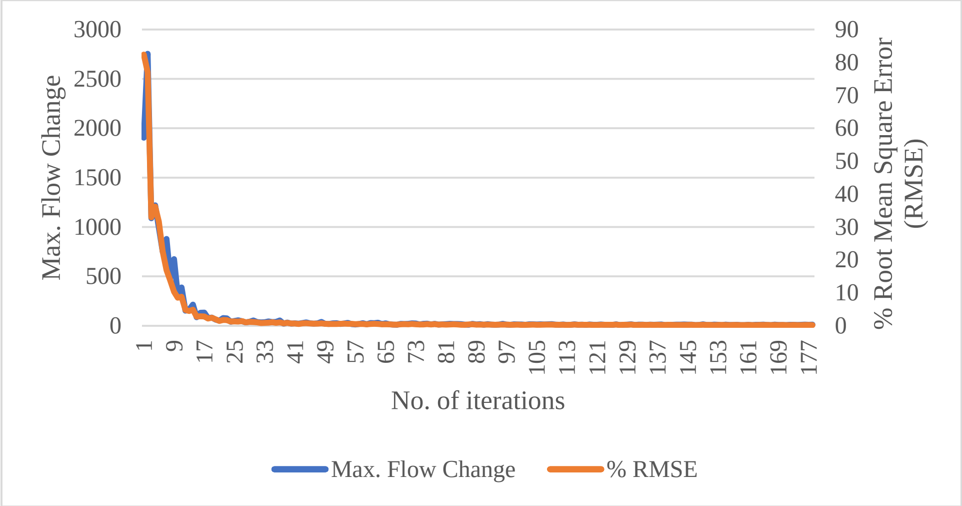


Figure 28 Model performance for paratransit network calibration

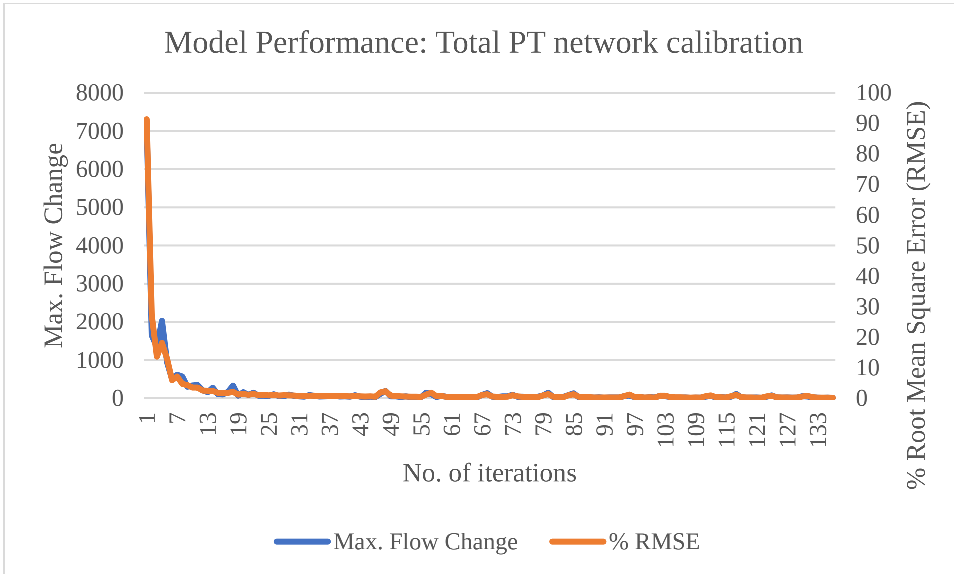


Figure 29 Model performance for public transport network calibration

6.3 Frequency optimisation

The city bus services of Visakhapatnam connect various interior and suburban parts of the city with its Central Business District (CBD). On the other hand, paratransit operators organize themselves around 18 high-demand corridors in the connecting various high demand nodes in the city. Intra city buses in Visakhapatnam operate along 92 intra-city routes, as explained above. These were further condensed to 83 routes for the sake of analysis This was because some routes had similar alignment but have different routes names according to the depot to which they were attached. Therefore, such reduction in routes will only reduce the number of variables for analysis, but will not impact the travel demand or network aspects.

APSRTC reviews and updates its route frequencies on a monthly basis while in case of paratransit, each vehicle operates on its own without any central planning system. The paratransit vehicles provide on-demand services on high-demand routes and are flexible to switch between various routes based on the users' travel needs. Due to lack of any co-ordination between the two systems in planning their routes and frequencies, they often compete for ridership on high demand corridors rather than complimenting each other to increase overall public transport service in the city. Hence, the transit assignment based frequency optimisation approach explained in Chapter 3 was applied to identify the optimal frequencies of the systems to meet the overall public transport demand in the city while minimising their total operational costs. This can further help each of the systems in re-organising their services such that they complement each other. Therefore, the Integer Linear Programming (ILP) based frequency optimisation methodology explain in Section 3.4 was applied for the transit network of Visakhapatnam.

6.3.1 Mathematical Modelling using CPLEX

The results of transit assignment for the calibrated network presented in the previous section were used as the input for frequency optimisation. Transit flows for the peak hour of the day i.e. 8-9 AM were used to determine the maximum bus and paratransit fleet required for the public transport demand in the city. IBM ILOG CPLEX (academic version 12.7.1), a commercial solver for integer programming problems, is applied for the analysis. Parameters like link wise traffic flow, travel time on each link and vehicle capacity are exported from TransCAD to excel and used as input to CPLEX. The frequency optimisation model explained in section 3.4 was coded in CPLEX such that it can take the link-wise transit flows and convert them to route-wise demand using the iterative process explained for the illustrative example in section 3.5. Inputs like cost of operations and layover time were derived from secondary data from the bus and paratransit operators. Table 35 summarises the inputs used for the frequency optimisation model. CPLEX takes these inputs from excel and write the outputs back in the same excel file.

Table 35 Inputs to frequency optimisation of bus and paratransit fleets

Inputs to frequency optimisation	**Data/ Source**
Link Flow	Transit assignment model/ TransCAD
Link Speed	Transit assignment model/ TransCAD
Link Travel time	Transit assignment model/ TransCAD
Vehicle capacity	60 passengers/ bus and 5 passengers/ three wheeled auto-rickshaw (paratransit)
Route length	Secondary data & Link Vs route mapping
Operational cost/km	20 Indian Rupees (INR)/km for Bus and 3 INR/km for paratransit (secondary data)
Layover time	5 min for both bus and paratransit
Passenger Car Units (PCU)	3 for Bus and 1 for paratransit
$PM_{2.5}$ emission factor (gm/km)	0.571 gm/km for bus and 0.109 gm/km for paratransit (Emissions, 2018)

Validation of the frequency optimisation model using base bus frequencies

The route wise frequencies and the vehicle fleets required to provide these services were derived for both Bus and paratransit systems. In order to validate the CPLEX model, the problem is initially solved by deriving the fleet requirements for the existing bus trips and paratransit trips separately. Given that both the services currently operate independently and are catered by their existing bus fleets, the output from the optimisation exercise was matched with their existing operations i.e. 83 bus routes and 18 paratransit routes separately to validate the results. It was observed that the output from the optimisation exercise matched with the real-world bus and paratransit operations at a load-factor of 2 i.e. the buses and paratransit systems are currently operating at twice their desired capacity during the peak hour. This observation also matched with the secondary data on vehicular occupancy reported by LCMP 2014. Therefore, the CPLEX model for frequency optimisation was validated.

6.4 Public transport demand and supply scenario analysis

The validated bi-level model was then used to analyse alternative scenarios of public transport demand and supply in the city as explained in section 3.5. Various travel demand and public transport supply scenarios have been analysed in comparision to the existing scenario to quantify the relative impact of moving towards integrated planning and operation of bus and paratransit systems. The definitions of various input and output variables of the scenario analysis are explained in sections 3.4 and 3.5.

Scenario 1: Integrated planning scenario: Combined transit assignment and optimisation

Scenario 1 analysed the impact of bus and paratransit services operating as an integrated services i.e. their frequencies being assigned as a combined service rather than the current scenario where they operate as two parallel services. To test this scenario, the Origin-Destination (OD) matrices of bus and paratransit users were combined to derive the total public transport OD. This OD was given as the input for transit assignment in TransCAD. The transit network input in TransCAD was modified as a total of 101 routes combining 83 bus routes and 18 paratransit routes. The bi-level transit assignment and frequency optimisation as proposed in section 3.4 and demonstrated in section 6.3 was used to analyse this scenario. The transit assignment was carried out for these

OD and network characteristics to derive the link wise travel demand. This demand was further split across the bus and paratransit routes on each link to derive their optimal frequencies in CPLEX. The optimal frequencies were used to arrive at the system costs for operators, travel time implications for users along with the road space requirements and emission implications as explained in section 3.4.

It was observed that planning for integrated frequencies across bus and paratransit can result in a marginal decrease in bus fleet needs but a significant reduction in paratransit needs to serve the overall public transport demand. Therefore, such a scenario is likely to result in 23% lesser operational cost and 70% lesser travel time compared to the current scenario. It is also likely to result in a 47% reduction in road space needs and 53% reduction in $PM_{2.5}$ emissions from public transport.

Scenario 2: Demand shift scenarios: Increasing bus share of transit demand

The user characteristics analysis presented in section 5.1.3 established user preference for paratransit systems for shorter trips while the buses are preferred for the longer trips. However, limited availability of bus systems in many parts of the city competing with high frequency paratransit services led to users' choosing paratransit services even for trips longer than 5 km. We tested for scenarios where the bus services improve and users choose them for longer trips in incremental shifts of 20% in each scenario i.e. shifts of 20%, 40%, 60%, 80% and 100% of paratransit trips longer than 5 km shifting to buses. The OD matrices were derived for each of the scenarios and were assigned to the combined transit network proposed in scenario 1. The bi-level transit assignment and frequency optimisation were carried out for these scenarios to derive the impacts on operational cost, user travel time, road space needs and emission implications for the city as explained previously.

It was observed that increased bus share of public transport in longer trips will have a positive impact on the city with a likely reduction of up to 36% in road space requirements and 29% emissions from public transport in a 100% shift scenario. The total travel time incurred by users is likely to be similar across demand shift scenarios. The total cost of operations of public transport have also reduced with increasing bus shares. However, the cost of operations of the bus system have increased due to the increased bus fleet requirements to cater to the demand. The analysis shows that achieving the road space and emission benefits of increased bus usage will require the city to increase its investments in public transport to support their increased operational expenses.

Scenario 3: Supply shift scenarios: Trunk and feeder system for bus and paratransit

The current scenario tests alternative public transport supply scenarios. The comparative analysis of bus and paratransit analysis presented in section 5.2 highlights how paratransit operations are currently focussed in the high demand areas of the city while bus services have a larger network coverage offering services across the city. Through this scenario we tested the impact of role reversal for bus and paratransit service i.e. buses operating exclusively on short but high demand routes, while paratransit operates as a feeder service operating across the city. Additionally, the impact of providing only one of bus or paratransit services throughout the existing public transport network to cater to the total transit demand in the city were tested in this scenario. It is to be noted here that the impact of changing supply mix of public transport modes on the remaining traffic i.e.

private modes has not been modelled as a part of this study. The following are the key findings of the supply shift scenario analysis:

- **Bus as trunk and paratransit as feeder**: The scenario of buses operating as a trunk service with paratransit being the feeder mode is likely to result in 32% reduction in road space requirements and 23% reduction in emissions compared to the base case scenario, for the peak hour scenario modelled for the current study. The operational characteristics analysis of paratransit presented in Chapter 5 shows that paratransit operators only operate an average of 10 hours a day i.e. during the morning and evening peak hours compared to 16 hours of service provided by buses. Therefore, in spite of the benefits offered during peak hours, it may not be recommended to restrict buses only to the high demand corridors, thereby negating public transport services to many areas during off peak hours
- **Bus only scenario**: A bus only public transport system is likely to achieve an 70% reduction in road space requirements of transit, 54% reduction in its emissions and 83% reduction in total cost of public transport operation compared to the current system of a mix of bus and paratransit services. However, the cost of operations for the public bus operator will increase significantly compared to the existing scenario. Additionally, realising the level of bus service supply needed in this scenario will require significant additional capital investment in bus fleet augmentation and its support infrastructure needs. The scenario will also add significantly to the users' travel time since buses will involve longer access and egress times compared to paratransit services.
- **Paratransit only scenario**: A paratransit only network will result in the opposite result to the bus only network i.e. the road space requirements are likely to increase by 18%, and the total

cost of operations by 94%. However, this scenario will result in significant travel time benefit to the users due to the high frequency services offered by paratransit

Scenario 4: Mass transit scenario: Bus Rapid Transit (BRT) along high demand corridors

The likely impact of providing mass transit in the form of a Bus Rapid Transit (BRT) along 80 km of the 210 km bus route network was modelled. Such a system would reserve an exclusive lane for bus operations, thereby increasing bus speed on the corridor by 25%. An open BRT system that allows the existing bus routes to enter and leave the corridors at various points was modelled. An integrated public transport demand OD matrix was used for transit assignment and frequency optimisation for this network. It was observed that such a system will attract a higher share of bus ridership within the overall public transport trips, thereby reducing the total road space requirements by 30% while also reducing operational cost by 24% by shortening the round trip time of buses. The total travel time of users is likely to decrease by 81% compared to the current scenario. The total travel time of users is likely to increase due to the increased wait times associated with bus trips. Achieving such a scenario will also require significant investments from the city Government towards creating the BRT infrastructure. However, the bus fleet required and the operational cost to cater to the increased demand is lesser because of the reduced round trip time of buses along the bus priority corridors. Cities can carry out similar analysis to analyse the payback period of creating BRT infrastructure.

Figure 30 to Figure 35 present the various results obtained in through the scenario analysis. Figure 30 presents the sum of route-wise bus frequencies and the fleet needed to meet these frequencies to estimate the buses needed for the entire bus network. Figure 31 presents the sum of route-wise paratransit frequencies and their fleet needed to meet these frequencies. Figure 32 presents the total vehicle hours of travel time spent by users in each of the scenarios tested while Figure 33 presents the cost of operations of bus and paratransit services in these scenarios. Finally Figure 34 and Figure 35 provide the impacts on the society i.e. road space requirement and PM emissions of the combined operation of buses and paratransit services. Table 36 summarises the results from the integrated optimisation scenarios and its comparision with the total of separate bus and paratransit optimisation.

6.5 Summary of transit assignment and frequency optimisation analysis

This chapter presented a framework for integrated planning of formal transit and informal paratransit services and demonstrated it for the case city of Visakhapatnam. The details of the travel demand modelling, transit assignment and frequency optimisation were presented in the previous sections. The following are the key findings from the analysis:

- The bi-level transit assignment and optimisation framework developed through this thesis, quantifies the benefits of integrated planning of city bus and paratransit systems. For a given transit demand, it presents a method of determining the optimal route level frequency and fleet requirements, travel time impact on users, cost to operators and impact on city in terms of road space requirements and particulate matter (PM 2.5) emissions
- Four alternative demand and supply scenarios have been tested using the bi-level framework. Based on the results of these four scenarios, it can be concluded that increasing the bus share of public transport is likely to derive more benefits for the city by reducing the road space requirements and emission implications of the public transport system. However, it is also likely to increase the access and egress travel time to be spent by users

- Choosing between either of the two modes isn't recommended because they offer different benefits to the users i.e. paratransit provides demand responsive and high frequency services during peak hours while buses provide assured services throughout the day

Therefore, cities should continue operating both formal public transport and paratransit systems and retain the benefits they offer. The ideal mix between the modes in a city can be determined dynamically for changing travel demand using the proposed framework, thereby balancing the users' and operators' priorities, while also minimising their road space requirements and emission implications.

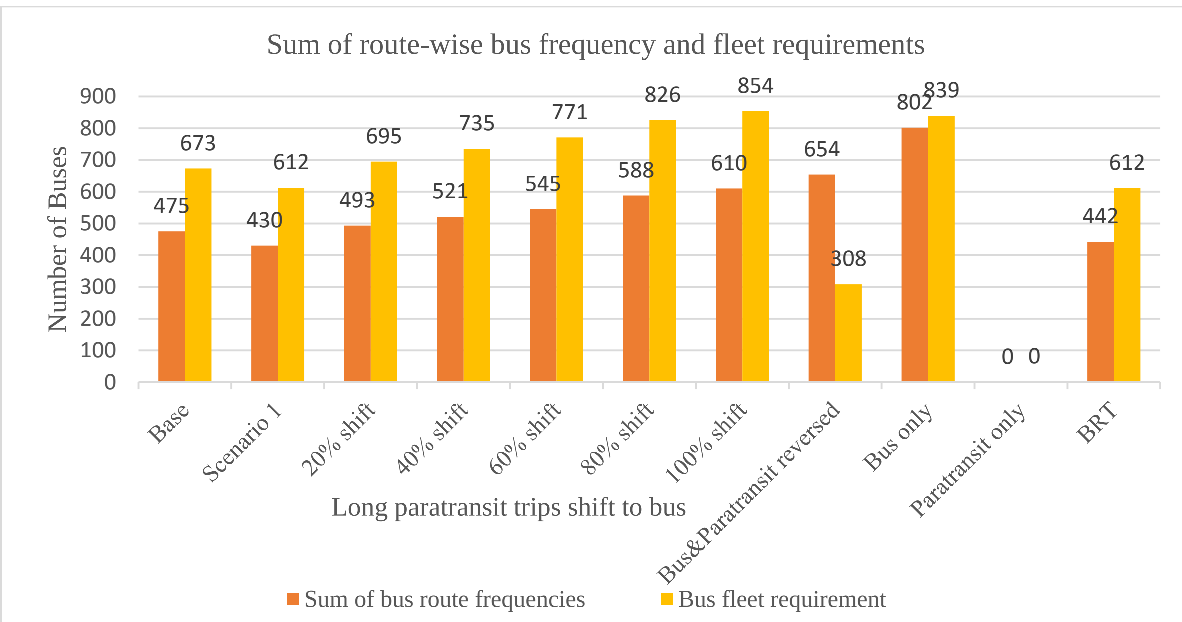


Figure 30 Sum of route-wise bus frequency and fleet requirements across scenarios

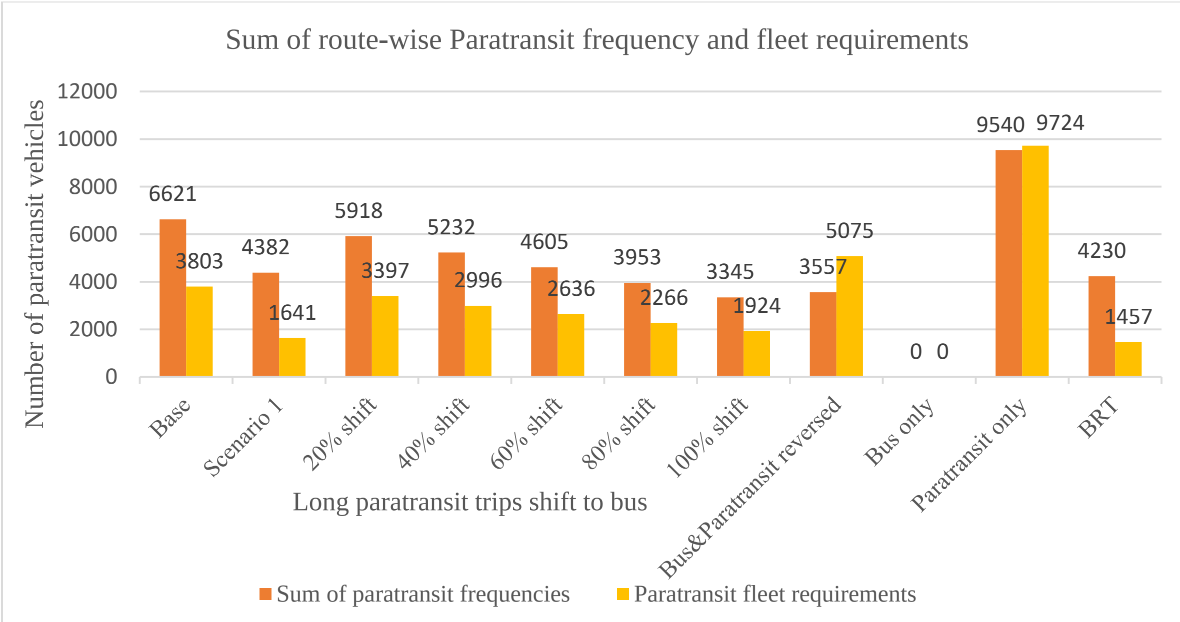


Figure 31 Sum of route-wise paratransit frequency and fleet requirements across scenarios

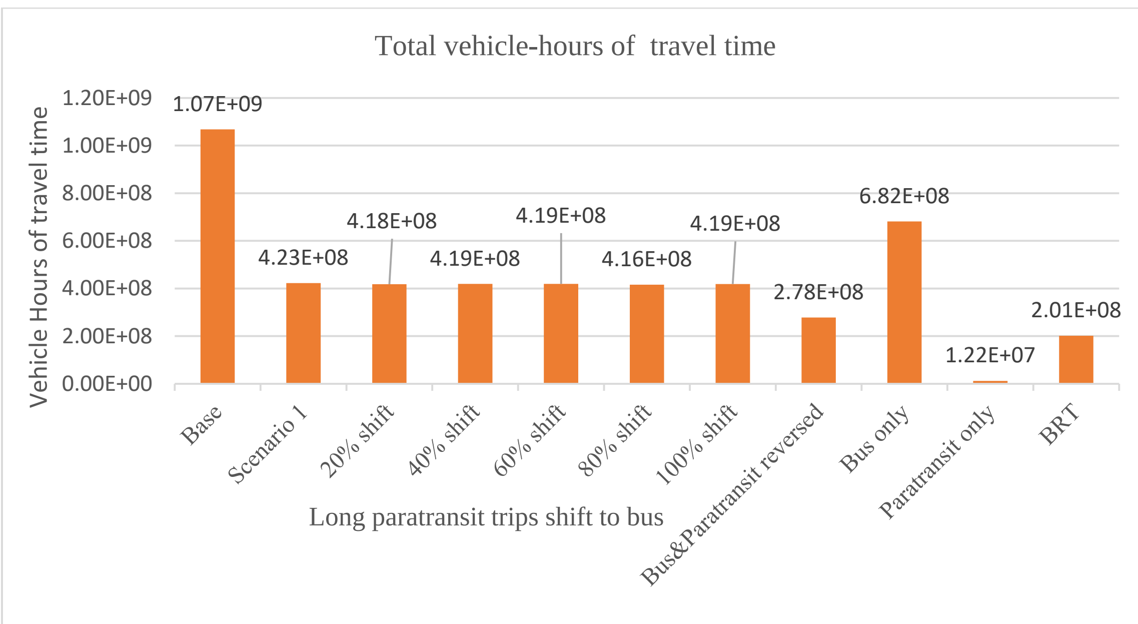


Figure 32 Total vehicle hours of travel time spent by users across scenarios

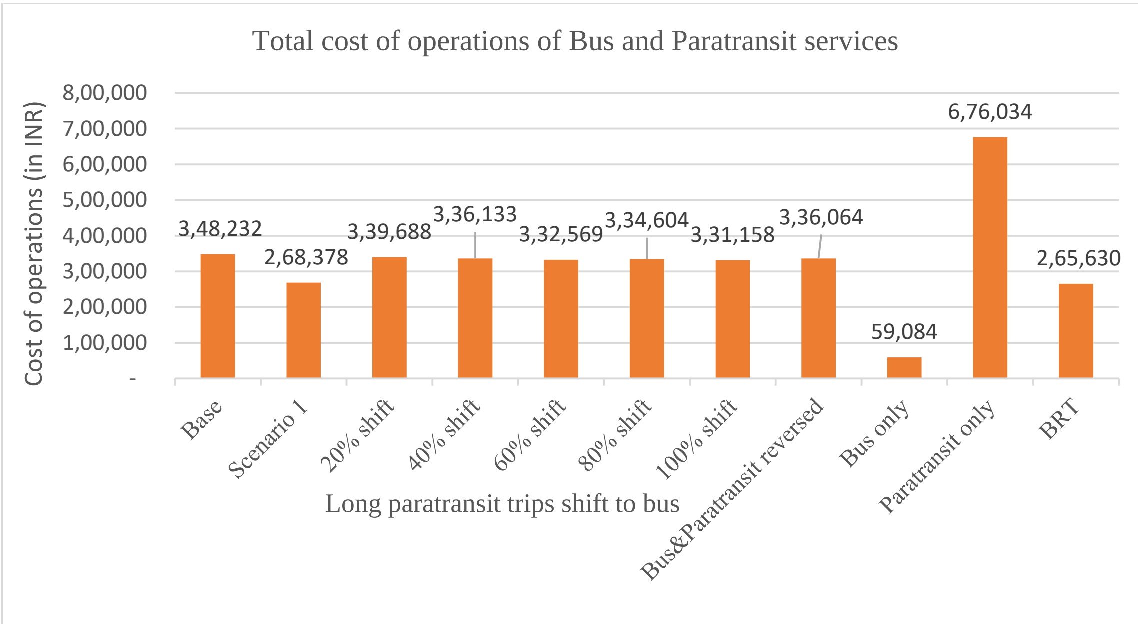


Figure 33 Total cost of operations of bus and paratransit operations across scenarios

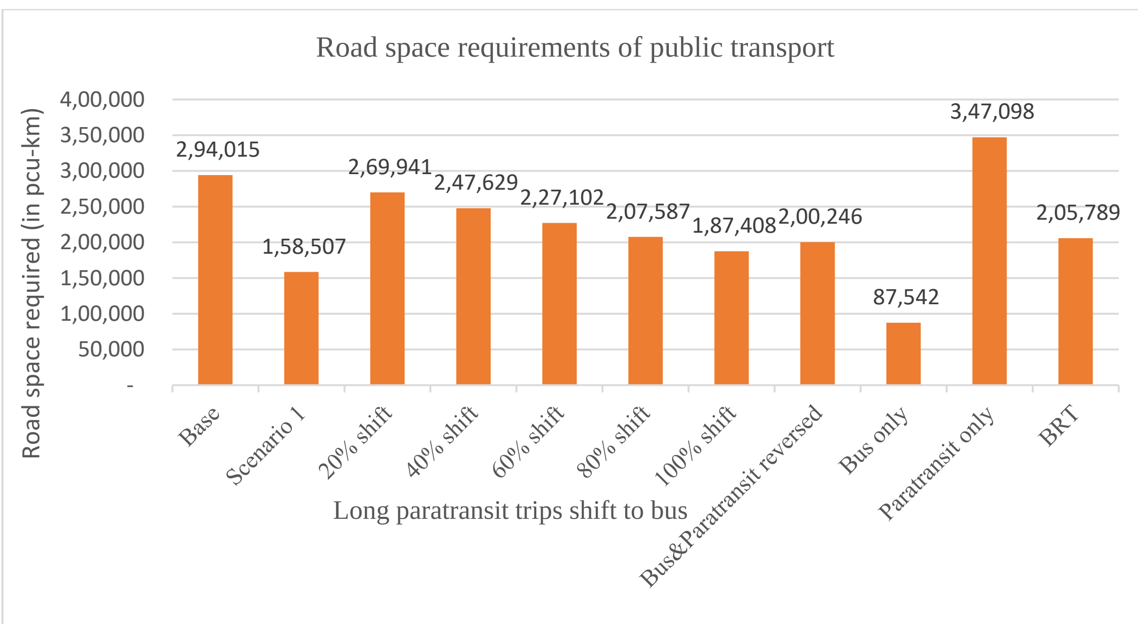


Figure 34 Road space requirements of bus and paratransit operations across scenarios

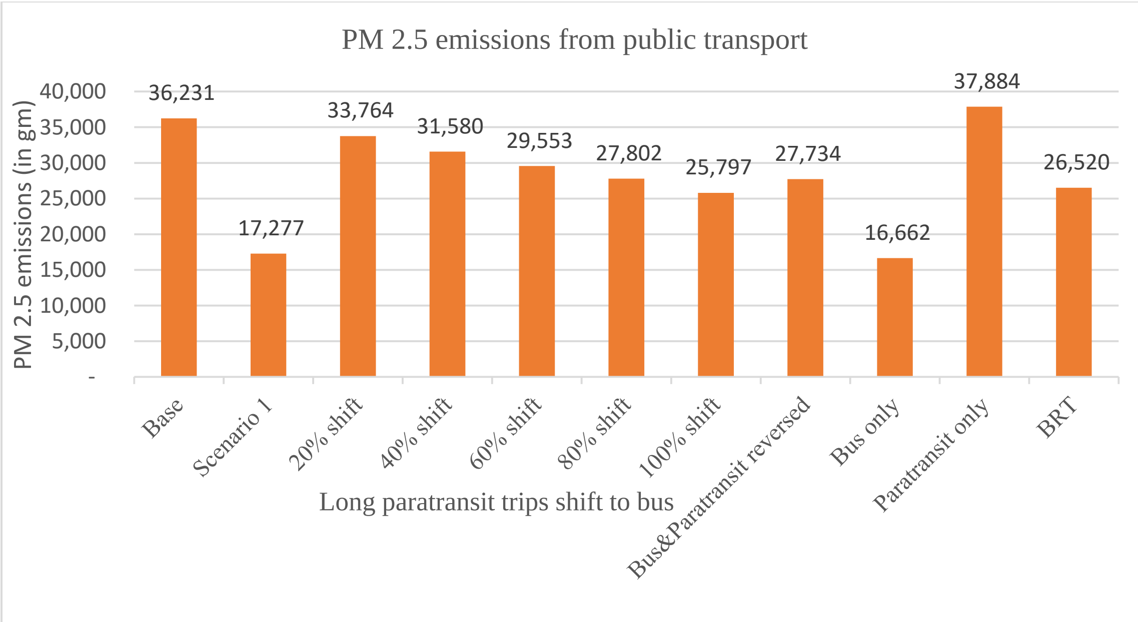


Figure 35 Particulate Matter (PM) emissions from bus and paratransit operations across scenarios

Table 36 Summary of results from scenario analysis

Name of Scenario	**Base network**: Separate assignment and frequency optimisation	**Scenario 1** Integrated assignment & optimisation	**Scenario 2: Demand shift scenarios**- longer paratransit trips shift to bus 20% shift	40% shift	60% shift	80% shift	100% shift	**Scenario 3: Supply shift scenarios** Bus, paratransit reversed	Bus only	Paratransit only	**Scenario 4: Mass transit scenario** BRT
Bus frequency requirements	475	430	493	521	545	588	610	654	802	0	442
Bus fleet requirements	673	612	695	735	771	826	854	308	839	1	612
Paratransit frequency requirements	6621	4382	5918	5232	4605	3953	3345	3557	0	9540	4230
Paratransit fleet requirements	3803	1641	3397	2996	2636	2266	1924	5075	0	9724	1457
Cost of operations	3,48,232	2,68,378	3,39,688	3,36,133	3,32,569	3,34,604	3,31,158	3,36,064	59,084	6,76,034	2,65,630
Vehicle hours of travel time	1.07E+09	4.23E+08	4.18E+08	4.19E+08	4.19E+08	4.16E+08	4.19E+08	2.78E+08	6.82E+08	1.22E+07	2.01E+08
Road space requirements (PCU-km in peak hour)	2,94,015	1,58,507	2,69,941	2,47,629	2,27,102	2,07,587	1,87,408	2,00,246	87,542	3,47,098	2,05,789
Particulate matter emissions (PM 2.5)	36,231	17,277	33,764	31,580	29,553	27,802	25,797	27,734	16,662	37,884	26,520

7 Conclusions and Recommendations

This thesis presents a framework for integrated planning of public transport systems in developing countries like India, which comprise of a mix of formal transit systems like metro / bus systems and informal shared transport systems like three-wheeled auto-rickshaws, minibuses etc.- popularly known as paratransit or Intermediate Public Transport (IPT) systems. The paratransit services which provide route/ corridor based services similar to formal public transport were analysed while the point to point taxi like services were beyond the scope of this thesis. The formal transit systems currently plan for their own services and without integration with paratransit systems. As a result, paratransit typically operates as independent service competing with public transport for ridership rather than complementing it. Majority of the limited literature available on the topic emphasises on designing paratransit as a feeder service to main-haul public transport systems. However, such arrangements haven’t worked in practice due to the inconvenience caused to both users and operators. Users need more transfers to shift from feeder to main-haul transit while paratransit operators are pushed to feeder services which have lesser demand compared to the trunk corridors. Additionally, the paratransit systems in India and other developing countries are in existence for many years, older than formal transit systems in many cases. Realigning their routes can be disruptive to the city’s mobility patterns. Therefore, a tactical planning approach where the existing formal transit and paratransit services are integrated through a frequency optimisation approach is identified to be more appropriate. Such an approach would ensure retaining the demand responsive nature of paratransit services while complementing the fixed schedule nature of formal transit systems.

A comprehensive planning framework was developed to understand the relative characteristics of formal and informal systems. This included user and operator characteristics of the two systems providing parallel services in the same city, even though with limited integration. The outputs from this analysis were used as inputs to the bi-level transit assignment and frequency optimisation model which carries out integrated transit assignment of bus and paratransit trips in the lower level and optimises the frequencies of these services on each route such that the overall cost of providing these services is minimised. The outputs from the bi-level model were then used to analyse and quantify the impact of altering the mix of formal and informal transit systems in a city. The model was applied for the case of Visakhapatnam, a medium sized Indian city with 2 million inhabitants and was used to test four alternative public transport scenarios for the city. Various demand and supply mixes for bus and paratransit services were analysed to quantify their impact on the users, operators and their overall impact on the city. The key conclusions from the research and recommendations for building on this in the future are explained below.

7.1 Findings from the user characteristics' analysis

The thesis presented a comprehensive framework to understand public transport user behaviour in the context of cities in developing countries which are served by both formal public transport systems and informal paratransit systems. The methodology for data collection and analysis of public transport user characteristics and their mode-choice behaviour in such contexts is presented. Home-based interview surveys, which were identified as the best method to develop the activity diaries of transit users across modes, were carried out for the city of Visakhapatnam, India. The detailed profile of user characteristics of the two public transport modes in the city i.e. the formal city bus system and the informal shared auto-rickshaw services that provide paratransit services were established.

A comparative analysis of their characteristics revealed that most of the socio-economic and travel characteristics of city bus and paratransit users were significantly different. Such differences indicate that the two modes cater to separate sets of public transport users within the city. Therefore, cities should recognise the key role played by paratransit in providing shared services to users. For e.g. in case of Visakhapatnam, citizens from the lower-income groups, female passengers, those having shorter trip lengths, access and egress times have a higher preference for the paratransit services currently.

A binary logistic regression analysis was carried out to understand the trend and intensity of the role of various socio-economic and travel variables in determining the users' mode-choice. While most of the user characteristics are different for bus and paratransit, not all variables showed significant correlation in impacting their mode choice. Socio-economic variables like gender, income and to a lesser extent-age were observed to have a correlation with mode choice. All the travel time components i.e. access and egress time, waiting time and in-vehicle time have a significant correlation towards mode-choice. Within travel time, wait time at the stops is observed to be more the component with most significance followed by access time and in-vehicle time. Paratransit was observed to be the preferred mode for short trips due to their high frequency services while bus was preferred for longer trips and trips where higher waiting times were acceptable.

The analysis indicates that the overall public transport mode share in the city can be maximized by minimising waiting time for users through operating the two modes such that they provide complimentary services catering to their specific set of users. This will require moving away from the current practice of competing for ridership by operating similar service. Therefore, bus and paratransit supply frequency needs to be planned in an integrated manner such that bus services are optimized for longer and high wait time trips while paratransit continues to provide high frequency services for the shorter trips.

7.2 Findings from the operators characteristics' analysis

Formal systems like city buses are planned and managed by a designated agency while paratransit systems are privately operated and not recognised by the Government as a formal mode of shared services. While majority of the literature covers policy, regulatory and institutional measures to integrate these two services, the understanding of their relative operational characteristics is limited. The current thesis addresses this gap in literature by presenting the operational characteristics and efficiency comparision of the formal bus and paratransit systems in the city of Visakhapatnam. A Data Envelopment Analysis (DEA) based approach was adopted for the first time to measure the operational efficiency of the two systems. Vehicle capacity and daily mileage were considered as the input variables while ridership and revenue were considered as the outputs. Paratransit was observed to have a higher efficiency compared to buses, probably because of their demand responsive operations.

It was also observed that while these two systems provide shared mobility services, they perform varying roles in catering to the city's travel needs. The city bus system operates with a service motive i.e. to maximise access to mobility for the citizens. Towards this, the bus system provides assured service for 16 hours every day, has a network reach throughout the city and carries three times more passengers than the paratransit system. The paratransit system operates with a business motive i.e., to maximise the revenue through their operations, which is in contrast to the service objectives of the bus system. Therefore, they operate only during peak hours and along high demand corridors, in parallel to the buses. However, their small vehicle size, short route lengths and unscheduled operations allow paratransit vehicles to switch between routes dynamically whereas buses provide fixed schedule services through the day. Such contrast in operational characteristics has led to buses being the main haul shared transport system of the city while paratransit augments their services by catering to the unmet public transport demand on high demand corridors through demand responsive services. Therefore, both bus and paratransit systems are crucial to achieve high shared transport shared in Indian cities.

Despite being the main haul service, the overall performance efficiency of the bus system is relatively lower on indicators like occupancy ratio and revenue per km. While this is partly because of buses operating in non-peak hours over a wider network coverage, another key reason is that the operational plans of the bus system only monitor the historical operational performance of the various routes and do not consider the developmental patterns and ever-changing travel demand requirements in the city. Our analysis clearly established that the occupancy and unit revenue generated per km of operation are not well correlated to parameters like route length, buses allocated to these routes and the mileage of these buses. Therefore, the bus system needs to update its operational planning and data maintenance practices to consider user demand and perception related attributes in addition to the physical performance attributes, to make itself more demand responsive thereby improving its occupancy and revenue performance.

The formal and informal public transport systems currently operate in silos, thereby acting as a competition to each other. An alternative approach where the Government recognises paratransit as a formal mode of transport needs to be adopted. An integrated planning and operations framework that optimises the bus and paratransit services in the city, where the assured bus services are complemented by the flexibility and demand responsiveness of paratransit will lead to an improved overall level of service of public transport.

The findings from this study can inform future policy discussions on integrating formal transit and paratransit systems.

7.3 Conclusions from transit assignment and frequency optimisation analysis

The thesis presents a framework for integrated and demand responsive transit frequency optimisation in cities with multi-modal public transport environments that include both formal and informal systems. It also tests the various alternative demand-supply scenarios of bus and paratransit integration to measure their impact on the society. A stand-alone bi-level optimisation approach has been adopted that solves for transit assignment at the lower level and uses the outputs from the assignment i.e. the link loads to optimise for the bus and paratransit system frequencies at the upper level model.

The transit assignment using user-equilibrium method was proposed while the frequency optimisation was solved using integer programming method that minimises cost of public transport operations subject to constraints like meeting link-level demands, the route frequencies matching the maximum load section on a given route and the fleet availability constraints for the bus and paratransit systems in the city. The modelling approach has been demonstrated for the real-world case of Visakhapatnam, a medium sized Indian city with both formal and informal modes of public transport.

7.4 Inferences from alternative demand and supply scenarios

The bi-level transit assignment and frequency optimisation model has been used to demonstrate the impact of various demand and supply scenarios in the city and their impact on users' using travel time, on operators using total cost of public transport operations and on the city using road-space requirements of the system and its environmental impact in terms of the overall particulate matter (PM 2.5) emissions caused by bus and paratransit systems together.

It was demonstrated that integrated planning for bus and paratransit will result in benefits to users, operators and also the city. Increasing bus share of public transport demand is likely to reduce operational costs, road space requirement and emissions without significant increase in users' travel time. Therefore, cities should invest more in improving their formal public transport systems. Conversely, a shift towards paratransit is likely to reduce users' travel time but will increase the cost of operations of the system, its road space requirement and emission impact. Finally, the mass transit scenario demonstrated the benefits of introducing Bus Rapid Transit (BRT) systems in such cities as it will result in improvement across user, operator and city level indicators.

It is recommended that both bus and paratransit systems are retained by cities even in the future. The integration between these modes should be planned in such a way that buses provide assured connectivity to the entire city throughout the day, while paratransit is used to cater to the additional demand during the peak hours. Formal public transport can be used to provide connectivity between well-established routes while paratransit can be used as a flexible and demand responsive system providing connectivity to areas beyond formal transit coverage.

7.5 Scope for future extension

7.5.1 Improvements to the transit assignment and frequency optimisation model

The current thesis carried out transit assignment using travel time as the key impedance metric. This was based on the binary logistic regression analysis for mode-choice between bus and paratransit systems. To apply the model in a more generalised context for other cities, cost of travel may also be added as an impedance factor.

The frequency optimisation model has used unit operating cost per km for bus and paratransit services. The model may be extended specifically for formal public transport services by adding further split of the cost to include staff cost, fuel cost, maintenance and administrative costs separately to understand the sensitivity of each of these variables on the objective function and decision variables. Similarly the route-wise travel time inputs in the model can be more accurate using big data analysis methods that incorporate GPS based vehicle tracking data from buses.

A further extension of the frequency optimisation model can be to apply it for electric vehicles by building in additional vehicle technology related constraints like daily range of the vehicle, time required for charging and its impact on the frequency and fleet needs of the city.

7.5.2 Scaling up the research to other cities in the developing world

Future extensions of this thesis can scale up the findings from the case city of Visakhapatnam to several other cities in India and other developing countries with similar public transport systems. Such comparative analysis across cities and countries can shape the global outlook towards integrating paratransit services with public transport systems.

The transport planning outlook of the current thesis focussed on user characteristics and operational characteristics of formal and informal transport systems. These transport planning outputs can be studied in relation to the policy and regulatory framework under which these systems are operating. Such an analysis can potentially provide insights into policy, planning and regulatory measures needed to integrate formal and informal public transport systems in Indian cities and other developing countries.

7.5.3 Extending paratransit analysis to include taxi based on-demand mobility

The current thesis considered on shared services operating shuttle services along corridors while the taxi services providing point to point services weren't considered. Future extensions of this work may study the relative characteristics between point to point and shared paratransit services. At the same time the recent emergence of on-demand taxi services provided by Taxi Network Companies (TNCs) like Uber and Ola add a new dimension to the shared mobility ecosystem. The current thesis' framework of user and operator characteristics analysis may be replicated for emerging new mobility services to develop a similar framework to analyse their impact on existing modes and to integrate them with existing formal and informal services.

7.5.4 Extending the current research to incorporate rail based mass-transit systems

The optimisation framework developed in this thesis highlights the benefits of integrated planning of city bus and paratransit systems and provides a method of determining the optimal route level frequency in order to minimise the overall cost of public transport operations. The model includes various variables like vehicle size, network speed, system capacity, load factor etc. as inputs, thereby making it flexible enough to be applied in other circumstances as well. Therefore, the same integrated framework can be applied even for other multimodal transit environments. For eg. cities with metro systems or multiple bus operators, vehicle size categories etc. along with bus and paratransit services. Since the bi-level model also captures travel demand patterns of the city, it can be used to analyse the varying transit requirements of the city as its urban form evolves to derive the frequency and fleet requirements of various transit modes for the new demand patterns.

7.5.5 Informing research on shared and autonomous vehicles in developed countries

While the current thesis focussed on integrating fixed schedule public transport with the demand responsive services of paratransit in developing country contexts, a similar approach can also be extended to developed country contexts. The concept of Demand Responsive Transit (DRT) has been emerging in many developed countries where TNCs offer shared vehicle services of capacity u to 12 passengers per vehicles. Many on the autonomous bus trials are focussing on medium sized vehicle of this capacity. Since paratransit services are already offering demand responsive services with similar capacities, even though without the technology interface of TNCs, findings from paratransit operations can inform ongoing research on autonomous and shared vehicles in developed countries.

7.6 Key research contributions

This thesis proposed a framework for integrated planning of formal and informal transit services which will benefit Indian cities and other cities from the developing world having similar mix of services. To the best of our knowledge this is the only study to propose an integrated planning framework that treats paratransit as a parallel mode of service and not as a feeder to the formal public transport system.

The following are a few unique contributions of this thesis to international literature:

- Developed a methodological framework to establish disaggregated demand and supply comparision of formal and informal transport users and operators
- Established a comprehensive profile of public transport users in Indian cities, that included paratransit users and their relative differences with formal transit users

- Evaluated the operational efficiency of city bus and paratransit services using Data Envelopment Analysis (DEA) and identified the key gaps in operational planning of Indian bus systems
- Developed and calibrated an integrated public transport travel demand model using household surveys. An innovative transit assignment model was developed in TransCAD-the travel demand modelling software to assign paratransit and bus trips to the network simultaneously
- Proposed a framework for integrated planning of formal and informal public transport systems combining travel demand characteristics and operator characteristics
- Developed a bi-level frequency optimisation model that is demonstrated to work for a real-world case city using an integer programming framework. The model can be used to derive demand-responsive route wise frequency and fleet requirements of both bus and paratransit services and further to assess the societal impacts of the system in terms of its road space and emission implications
- The modelling framework segregates analysis for optimising user characteristics (transit assignment), operators' characteristics (frequency optimisation) and societal impact of the system (emissions and road space requirements) which allows for sensitivity analysis for each of the stakeholders. Majority of the literature are models these levels simultaneously thereby making it difficult to analyse the stakeholder wise impact of improving the system

8 References

AGARWAL, S., YADAV, S. P. & SINGH, S. 2010. DEA based estimation of the technical efficiency of state transport undertakings in India. *Opsearch,* 47**,** 216-230.

AIGNER, D., LOVELL, C. K. & SCHMIDT, P. 1977. Formulation and estimation of stochastic frontier production function models. *Journal of econometrics,* 6**,** 21-37.

BADAMI, M. G. & HAIDER, M. 2007. An analysis of public bus transit performance in Indian cities. *Transportation Research Part A: Policy and Practice,* 41**,** 961-981.

BADOE, D. & CHEN, C. 2004. Modeling trip generation with data from single and two independent cross-sectional travel surveys. *Journal of urban planning and development,* 130**,** 167-174.

BASUKI JOEWONO, T. & KUBOTA, H. 2008. Paratransit service in Indonesia: user satisfaction and future choice. *Transportation planning and technology,* 31**,** 325-345.

BEHRENS, R., MCCORMICK, D., ORERO, R. & OMMEH, M. 2017. Improving paratransit service: Lessons from inter-city matatu cooperatives in Kenya. *Transport Policy,* 53**,** 79-88.

BIEMER, P. P. & LYBERG, L. E. 2003. *Introduction to survey quality*, John Wiley & Sons.

BRONS, M., NIJKAMP, P., PELS, E. & RIETVELD, P. 2005. Efficiency of urban public transit: a meta analysis. *Transportation,* 32**,** 1-21.

CEDER, A. 1984. Bus frequency determination using passenger count data. *Transportation Research Part A: General,* 18**,** 439-453.

CEDER, A. 2009. Stepwise multi-criteria and multi-strategy design of public transit shuttles. *Journal of Multi-Criteria Decision Analysis,* 16**,** 21-38.

CEDER, A. 2013. Integrated smart feeder/shuttle transit service: simulation of new routing strategies. *Journal of Advanced Transportation,* 47**,** 595-618.

CEDER, A. 2016a. *Public transit planning and operation: Modeling, practice and behavior*, CRC press.

CEDER, A. 2016b. *Public transit planning and operation: Modeling, Practice and Behaviour*, CRC Press, Boca Raton, USA.

CEDER, A. A., HASSOLD, S. & DANO, B. 2013. Approaching even-load and even-headway transit timetables using different bus sizes. *Public Transport***,** 1-25.

CENSUS 2011a. Primary Census Abstract. *Census of India, Government of India.*

CENSUS 2011b. Provisional Population Totals: Urban Agglomerations and Cities. *Census of India, Government of India.*

CENSUS 2012a. Distance From residence to place of work and mode of travel to place of work - 2011. *In:* CENSUS OF INDIA, G. O. I. (ed.). India.

CENSUS 2012b. Provisional Population Totals Paper 2, Volume 2 of 2011 : Andhra Pradesh. *Census of India, Government of India.*

CEPEDA, M., COMINETTI, R. & FLORIAN, M. 2006. A frequency-based assignment model for congested transit networks with strict capacity constraints: characterization and computation of equilibria. *Transportation research part B: Methodological,* 40**,** 437-459.

CERVERO, R. 2000. *Informal transport in the developing world*, UN-HABITAT.

CERVERO, R. & GOLUB, A. 2007. Informal transport: A global perspective. *Transport policy,* 14**,** 445-457.

CHANG, K.-P. & KAO, P.-H. 1992. The relative efficiency of public versus private municipal bus firms: an application of data envelopment analysis. *Journal of Productivity analysis,* 3**,** 67-84.

CHENG, G. 2014. Data envelopment analysis: methods and MaxDEA software. Beijing: Intellectual Property Publishing House.

CODINA, E., MARÍN, A. & LÓPEZ, F. Modeling and optimization of frequencies on congested bus lines. Proceedings of the 14th international conference on Automatic Control, Modelling & Simulation, and Proceedings of the 11th international conference on Microelectronics, Nanoelectronics, Optoelectronics, 2012. World Scientific and Engineering Academy and Society (WSEAS), 104-109.

COELLI, T. 1996. A guide to DEAP version 2.1: a data envelopment analysis (computer) program. *Centre for Efficiency and Productivity Analysis, University of New England, Australia*.

CONSTANTIN, I. & FLORIAN, M. 1995. Optimizing frequencies in a transit network: a nonlinear bi-level programming approach. *International Transactions in Operational Research,* 2**,** 149-164.

DARAIO, C., DIANA, M., DI COSTA, F., LEPORELLI, C., MATTEUCCI, G. & NASTASI, A. 2016. Efficiency and effectiveness in the urban public transport sector: A critical review with directions for future research. *European Journal of Operational Research,* 248**,** 1-20.

DEB, K. & FILIPPINI, M. 2010. Public bus transport demand elasticities in India.

DEL MISTRO, R. & BEHRENS, R. 2015. Integrating the informal with the formal: An estimation of the impacts of a shift from paratransit line-haul to feeder service provision in Cape Town. *Case Studies on Transport Policy,* 3**,** 271-277.

DELL'OLIO, L., IBEAS, A. & CECIN, P. 2011. The quality of service desired by public transport users. *Transport Policy,* 18**,** 217-227.

DELL'OLIO, L., IBEAS, A. & CECÍN, P. 2010. Modelling user perception of bus transit quality. *Transport Policy,* 17**,** 388-397.

DELL'OLIO, L., IBEAS, A. & RUISÁNCHEZ, F. 2012. Optimizing bus-size and headway in transit networks. *Transportation,* 39**,** 449-464.

DESAULNIERS, G. & HICKMAN, M. 2007. Public transit. *Transportation, Handbooks in Operations Research and Management Science***,** 69-127.

DIKAS, G. & MINIS, I. 2014. Scheduled paratransit transport systems. *Transportation Research Part B: Methodological,* 67**,** 18-34.

EMISSIONS, U. 2018. *Air Pollution Knowledge Assessments (APnA) city program* [Online]. Available: http://www.urbanemissions.info/.

FERRO, P. S. & BEHRENS, R. Paratransit and Formal Public Transport Operational Complementarity: Imperatives, Alternatives and Dielemmas. 13th World Conference on Transport Research, 2013 Rio De Janerio, Brazil.

FERRO, P. S. & BEHRENS, R. 2015. From direct to trunk-and-feeder public transport services in the Urban South: Territorial implications. *Journal of Transport and Land use,* 8**,** 123-136.

FERRO, P. S., BEHRENS, R. & GOLUB, A. Planned and paratransit service integration through trunk and feeder arrangements: an international review. 31st Southern African Transport Conference (SATC 2012), 2012.

FRIEDRICH, M. & WEKECH, S. 2004. A schedule-based transit assignment model addressing the passengers' choice among competing connections. *Schedule-Based Dynamic Transit Modeling: theory and applications.* Springer.

FU, Q., LIU, R. & HESS, S. 2012. A review on transit assignment modelling approaches to congested networks: a new perspective. *Procedia-Social and Behavioral Sciences,* 54**,** 1145-1155.

FURTH, P. G. & WILSON, N. H. 1981. Setting frequencies on bus routes: Theory and practice. *Transportation Research Record,* 818**,** 1-7.

GADEPALLI, R. 2016. Role of Intermediate Public Transport in Indian Cities. *Economic & Political Weekly,* 51**,** 46-49.

GADEPALLI, R., JAHED, M., RAMACHANDRA RAO, K. & TIWARI, G. 2014a. Multiple Classification Analysis for Trip Production Models Using Household Data: Case Study of Patna, India. *Journal of Urban Planning and Development,* 140**,** 05013001.

GADEPALLI, R., JAHED, M., RAO, K. R. & TIWARI, G. 2014b. Multiple Classification Analysis for Trip Production Models using Household Data: Case study of Patna, India. *Journal of Urban Planning and Development*.

GADEPALLI, R. & RAYAPROLU, S. 2019. Factors affecting performance of urban bus transport systems in India: A Data Envelopment Analysis (DEA) based approach. *World Conference on Transport Research - WCTR 2019* Mumbai.

GALLO, M., D'ACIERNO, L. & MONTELLA, B. 2011. A multimodal approach to bus frequency design. *WIT Transactions on the Built Environment,* 116**,** 193-204.

GAO, Z., SUN, H. & SHAN, L. L. 2004. A continuous equilibrium network design model and algorithm for transit systems. *Transportation Research Part B: Methodological,* 38**,** 235-250.

GARCIA SANCHEZ, I. 2009. Technical and scale efficiency in Spanish urban transport: estimating with data envelopment analysis. *Advances in operations research,* 2009.

GOEL, R. & TIWARI, G. 2015. Access–egress and other travel characteristics of metro users in Delhi and its satellite cities. *IATSS Research,* 39**,** 9.

GOI 1950. Road Transport Corporations (RTC) Act. Government of India.

GROSFELD-NIR, A. & BOOKBINDER, J. H. 1995. The planning of headways in urban public transit. *Annals of Operations Research,* 60**,** 145-160.

GUEVARA, C. A. & THOMAS, A. 2007. Multiple classification analysis in trip production models. *Transport Policy,* 14**,** 514-522.

GUIHAIRE, V. & HAO, J.-K. 2008. Transit network design and scheduling: A global review. *Transportation Research Part A: Policy and Practice,* 42**,** 1251-1273.

GUTTIKUNDA, S. K., GOEL, R. & PANT, P. 2014. Nature of air pollution, emission sources, and management in the Indian cities. *Atmospheric Environment,* 95**,** 501-510.

GYMMY JOSEPH KATTOR, A. M. K. V., PRETINA GEORGE 2013. Analysis of Trip Attraction Characteristics of Commercial Land Use in Medium Sized Towns in Kerala. *International Journal of Innovative Technology and Exploring Engineering (IJITEE),* 3**,** 7.

HADAS, Y. & SHNAIDERMAN, M. 2012. Public-transit frequency setting using minimum-cost approach with stochastic demand and travel time. *Transportation Research Part B: Methodological,* 46**,** 1068-1084.

HAMDOUCH, Y. & LAWPHONGPANICH, S. 2008. Schedule-based transit assignment model with travel strategies and capacity constraints. *Transportation Research Part B: Methodological,* 42**,** 663-684.

HAN, A. F. & WILSON, N. H. 1982. The allocation of buses in heavily utilized networks with overlapping routes. *Transportation Research Part B: Methodological,* 16**,** 221-232.

HENSHER, D. A. & ROSE, J. M. 2007. Development of commuter and non-commuter mode choice models for the assessment of new public transport infrastructure projects: a case study. *Transportation Research Part A: Policy and Practice,* 41**,** 428-443.

HPEC 2011. The High Powered Expert Committee (HPEC) for Estimating the Investment Requirements for Urban Infrastructure Services. *Ministry of Urban Development, Government of India*

HUANG, Z., REN, G. & LIU, H. 2013. Optimizing bus frequencies under uncertain demand: Case study of the transit network in a developing city. *Mathematical problems in Engineering,* 2013.

IDRIS, A., HABIB, K. & SHALABY, A. 2014. Dissecting the role of transit service attributes in attracting commuters: Lessons from a comprehensive revealed preference-stated preference study on commuting mode-switching behavior in Toronto, Ontario, Canada. *Transportation Research Record: Journal of the Transportation Research Board***,** 107-117.

IMAZ, A., HABIB, K. M. N., SHALABY, A. & IDRIS, A. O. 2015. Investigating the factors affecting transit user loyalty. *Public Transport,* 7**,** 39-60.

IRC 1994a. Guidelines for the design of at-grade intersections in rural and urban areas. *Indian Roads Congress*

IRC 1994b. IRC SP 41: Guidelines for the design of at-grade intersections in rural & urban areas.

ITF, W., TERI 2018. India Urban Mobility Model. *In:* INTERNATIONAL TRANSPORT FORUM, W. B. G., THE ENERGY RESOURCES INSTITUTE (TERI) (ed.).

ITOH, S. & HATO, E. 2013. Combined estimation of activity generation models incorporating unobserved small trips using probe person data. *Journal of the Eastern Asia Society for Transportation Studies,* 10**,** 525-537.

ITRANS 2012. Organising the coordination and dissemination of research on urban transport. *In:* (IUT), I. O. U. T. (ed.).

ITRANS 2014a. Low carbon comprehensive mobility plan (LCMP) for Visakhapatnam. *Innovative Transport Solutions (iTrans) Pvt. Ltd.* New Delhi.

ITRANS 2014b. Low Carbon Mobility Plan (LCMP) for Visakhapatnam. Visakhapatnam: United Nations Environment Program (UNEP).

IUT 2014. Improving and Upgrading IPT Vehicles and Services: A Study. *In:* INDIA, I. O. U. T. I. (ed.).

JANSSON, J. O. 1980. A simple bus line model for optimisation of service frequency and bus size. *Journal of Transport Economics and Policy***,** 53-80.

JARA-DÍAZ, S., TIRACHINI, A. & CORTÉS, C. E. 2008. Modeling public transport corridors with aggregate and disaggregate demand. *Journal of Transport Geography,* 16**,** 430-435.

JARBOUI, S., FORGET, P. & BOUJELBENE, Y. 2012. Public road transport efficiency: a literature review via the classification scheme. *Public Transport,* 4**,** 101-128.

KHATTAK, A. J. & DE PALMA, A. 1997. The impact of adverse weather conditions on the propensity to change travel decisions: a survey of Brussels commuters. *Transportation Research Part A: Policy and Practice,* 31**,** 181-203.

KIM, M. E. & SCHONFELD, P. 2014. Integration of conventional and flexible bus services with timed transfers. *Transportation Research Part B: Methodological,* 68**,** 76-97.

KIM, W., SON, B., CHUNG, J.-H. & KIM, E. 2009. Development of real-time optimal bus scheduling and headway control models. *Transportation Research Record,* 2111**,** 33-41.

KOPPELMAN, F. S. & BHAT, C. 2006. A self instructing course in mode choice modeling: multinomial and nested logit models.

KOTSEMIR, M. 2013. Measuring national innovation systems efficiency–a review of DEA approach.

KRYGSMAN, S., DIJST, M. & ARENTZE, T. 2004. Multimodal public transport: an analysis of travel time elements and the interconnectivity ratio. *Transport Policy,* 11**,** 265-275.

KUHNIMHOF, T., BUEHLER, R., WIRTZ, M. & KALINOWSKA, D. 2012. Travel trends among young adults in Germany: increasing multimodality and declining car use for men. *Journal of Transport Geography,* 24**,** 443-450.

LE-KLÄHN, D.-T., GERIKE, R. & HALL, C. M. 2014. Visitor users vs. non-users of public transport: The case of Munich, Germany. *Journal of Destination Marketing & Management,* 3**,** 152-161.

MANI, A., PAI, M. & AGGARWAL, R. 2012a. Sustainable urban transport in India: role of the auto-rickshaw sector.

MANI, A., PAI, M. & AGGARWAL, R. 2012b. Sustainable urban transport policy in India: focus on Autorickshaw sector. *Transportation Research Record: Journal of the Transportation Research Board***,** 104-110.

MARTÍNEZ, H., MAUTTONE, A. & URQUHART, M. E. 2014. Frequency optimization in public transportation systems: Formulation and metaheuristic approach. *European Journal of Operational Research,* 236**,** 27-36.

MASSIMO, F. & KAUSHIK, D. 2010. Public bus transport demand elasticities in India. USI Università della Svizzera italiana.

MEEUSEN, W. & VAN DEN BROECK, J. 1977. Efficiency estimation from Cobb-Douglas production functions with composed error. *International economic review***,** 435-444.

MENG, X., ZHENG, L. & ZHANG, L. 2009. The Research of Household Probability Distribution and Trip Production Forecast Based on Trip Characteristics of Household. *Logistics: The Emerging Frontiers of Transportation and Development in China.*

MIN, H. 2013. Assessing the Comparative Efficiency of Urban Mass Transit Systems in Ohio: Longitudinal Analysis.

MIN, H., AHN, Y.-H. & LAMBERT, T. E. 2015. Evaluating the comparative efficiency of urban mass transit systems: a longitudinal analysis of the Ohio case. *International Journal of Logistics Research and Applications,* 18**,** 518-534.

MOHRING, H. 1972. Optimization and scale economies in urban bus transportation. *The American Economic Review,* 62**,** 591-604.

MOHUA. 2018. *Resource allocation for urban development* [Online]. Ministry of Housing and Urban Affairs. Available: http://pib.nic.in/newsite/PrintRelease.aspx?relid=176273 [Accessed May 05, 2018.

MOLNAR, J. & MESHEIM, L. 2010. A Disaggregate Analysis of Demand for Local Bus Service in Great Britain (excluding London) using the National Travel Survey. *Draft, University College London and Institute for Fiscal Studies*.

MORTH 2017a. Review of the performance of State Road Transport Undertakings *Ministry of Road Transport and Highways (MoRTH).*

MORTH 2017b. Road Transport Year Book 2015. *Ministry of Road Transport and Highways (MoRTH).*

MOSER, A., GADEPALLI, R. & FELLENDORF, M. 2016. Travel Demand in Emerging Countries: Analysis of Comprehensive Mobility Plans in India *Transportation Research Board 95th Annual Meeting.* Washington, D. C.

MOUD 2006. National Urban Transport Policy. *Ministry of Housing and Urban Affairs.*

MOUD 2011. Parameters for the National Mission on Sustainable Habitat (NMSH) *In:* TRANSPORT, S.-C. O. U. (ed.). Ministry of Urban Development, Government of India.

MOUD 2012a. Jawaharlal Nehru Urban Renewal Mission (JnNURM). *Ministry of Urban Development, Government of India.*

MOUD 2012b. Recommendations of Working Group on Urban Transport for 12th Five Year Plan. *Ministry of Urban Development , Government of India.*

MOUD 2013. Transforming City Bus Transport in India through Financial Assistance for Bus Procurement under JnNURM. *Ministry of Urban Development (MoUD), Government of India.*

MOUD 2014. Draft Concept Note on Smart Cities. *Ministry of Urban Development (MoUD).*

NEWELL, G. 1979. Some issues relating to the optimal design of bus routes. *Transportation Science,* 13**,** 20-35.

NOLAN, J. F., RITCHIE, P. C. & ROWCROFT, J. 2001. Measuring efficiency in the public sector using nonparametric frontier estimators: a study of transit agencies in the USA. *Applied Economics,* 33**,** 913-922.

NOR, M., GHANI, N., NOR, M., RAHIM, A. & ABDULLAH, A. Z. 2006. Predicting the impact of demand-and supply-side measures on bus ridership in Putrajaya, Malaysia. *Journal of Public Transportation,* 9**,** 4.

ORTÚZAR, J. D. & WILLUMSEN, L. G. 2011. *Modelling transport,* Wiley Chichester:.

ORTUZAR, J. D. D. & WILLUMSEN, L. G. 2014. *Modelling Transport,* Wiley.

PHUN, V. K. & YAI, T. 2016. State of the art of paratransit literatures in Asian developing countries. *Asian Transport Studies,* 4**,** 57-77.

PRETINA GEORGE, G. J. K. 2013. Forecasting trip attraction based on commercial land use characteristics. *IJRET: International Journal of Research in Engineering and Technology,* 2**,** 9.

PUCHER, J., KORATTYSWAROPAM, N., MITTAL, N. & ITTYERAH, N. 2005. Urban transport crisis in India. *Transport Policy,* 12**,** 185-198.

RASTOGI, R. & KRISHNA RAO, K. 2003. Travel characteristics of commuters accessing transit: Case study. *Journal of Transportation Engineering,* 129**,** 684-694.

SAMPAIO, B. R., NETO, O. L. & SAMPAIO, Y. 2008. Efficiency analysis of public transport systems: Lessons for institutional planning. *Transportation Research Part A: Policy and Practice,* 42**,** 445-454.

SAXENA, P. & SAXENA, R. R. 2010. Measuring efficiencies in Indian public road transit: a data envelopment analysis approach. *Opsearch,* 47**,** 195-204.

SCHÉELE, S. 1980. A supply model for public transit services. *Transportation Research Part B: Methodological,* 14**,** 133-146.

SEN, A. K., TIWARI, G. & UPADHYAY, V. 2010. Estimating marginal external costs of transport in Delhi. *Transport Policy,* 17**,** 27-37.

SHERMAN, H. D. & ZHU, J. 2006. *Service productivity management: improving service performance using Data Envelopment Analysis (DEA),* Springer science & business media.

SHITTU, A. 2014. Towards Quasi-Formal Management of Paratransit in Informal Transport Dependent Cities of Nigeria. *IOSR Journal of Humanities and Social Science (IOSR-JHSS),* 19**,** 75-80.

SILVER, S. 2013. Assessing the Comparative Efficiency of Urban Mass Transit Systems in Ohio: Longitudinal Analysis.

SINGH, S. K. 2005. Review of urban transportation in India. *Journal of Public Transportation,* 8**,** 5.

SPIESS, H. & FLORIAN, M. 1989. Optimal strategies: a new assignment model for transit networks. *Transportation Research Part B: Methodological,* 23**,** 83-102.

SRINIVASAN, K. K. & BHARGAVI, P. 2007. Longer-term changes in mode choice decisions in Chennai: a comparison between cross-sectional and dynamic models. *Transportation,* 34**,** 355-374.

STOPHER, P. R. & GREAVES, S. P. 2007. Household travel surveys: Where are we going? *Transportation Research Part A: Policy and Practice,* 41**,** 367-381.

SUMAN, H. K., BOLIA, N. B. & TIWARI, G. 2016. Analysis of the Factors Influencing the Use of Public Buses in Delhi. *Journal of Urban Planning and Development***,** 04016003.

SUMAN, H. K., BOLIA, N. B. & TIWARI, G. 2017. Comparing public bus transport service attributes in Delhi and Mumbai: Policy implications for improving bus services in Delhi. *Transport Policy,* 56**,** 63-74.

THAIMUTA, J. & MORONGE, M. 2014. Factors affecting the performance of matatu paratransit venture in small and medium enterprises in Nairobi County. *International Journal of Current Business and Social Sciences,* 1**,** 1-17.

TIWARI, G. 2002. Urban transport priorities: meeting the challenge of socio-economic diversity in cities, a case study of Delhi, India. *Cities,* 19**,** 95-103.

TROMPET, M., ANDERSON, R. & GRAHAM, D. 2009. Variability in comparable performance of urban bus operations. *Transportation Research Record: Journal of the Transportation Research Board***,** 177-184.

TROMPET, M., ANDERSON, R. J. & GRAHAM, D. J. 2018. Improved understanding of the relative quality of bus public transit using a balanced approach to performance data normalization☆. *Transportation Research Part A: Policy and Practice,* 114**,** 13-23.

TROMPET, M. & GRAHAM, D. J. A Balanced Approach to Normalizing Bus Operational Data for Performance Benchmarking Purposes. Transportation Research Board 91st Annual Meeting, 2012.

UITP 2017. Public Transport Trends. *In:* TRANSPORT, U. A. F. P. (ed.).

UN 2015. World Urbanisation Prospects: The 2014 Revision. *In:* UNITED NATIONS, D. O. E. A. S. E. P. D. (ed.).

UNDP. 2015. *Sustainable Development Goals* [Online]. United Nations Development Program (UNDP).

VAN LIEROP, D. & EL-GENEIDY, A. 2016. Enjoying loyalty: The relationship between service quality, customer satisfaction, and behavioral intentions in public transit. *Research in Transportation Economics,* 59**,** 50-59.

VEDAGIRI, P. & ARASAN, V. T. 2009. Modelling modal shift due to the enhanced level of bus service. *Transport,* 24**,** 121-128.

VERBAS, I. & MAHMASSANI, H. 2013. Optimal Allocation of Service Frequencies over Transit Network Routes and Time Periods: Formulation, Solution, and Implementation Using Bus Route Patterns. *Transportation Research Record: Journal of the Transportation Research Board***,** 50-59.

VERBAS, İ. Ö., FREI, C., MAHMASSANI, H. S. & CHAN, R. 2015a. Stretching resources: sensitivity of optimal bus frequency allocation to stop-level demand elasticities. *Public Transport,* 7**,** 1-20.

VERBAS, İ. Ö. & MAHMASSANI, H. S. 2015. Integrated Frequency Allocation and User Assignment in Multimodal Transit Networks: Methodology and Application to Large-Scale Urban Systems. *Transportation Research Record: Journal of the Transportation Research Board***,** 37-45.

VERBAS, İ. Ö., MAHMASSANI, H. S. & HYLAND, M. F. 2015b. Dynamic Assignment-Simulation Methodology for Multimodal Urban Transit Networks. *Transportation Research Record: Journal of the Transportation Research Board***,** 64-74.

VUDA 2007. Revised Master Plan for Visakhapatnam Metropolitan Region.

WASHINGTON, S. & WOLF, J. 1997. Hierarchical tree-based versus ordinary least squares linear regression models: theory and example applied to trip generation. *Transportation Research Record,* 1581**,** 82-88.

WENG, J., TU, Q., YUAN, R., LIN, P. & CHEN, Z. 2018. Modeling mode choice behaviors for public transport commuters in Beijing. *Journal of Urban Planning and Development,* 144**,** 05018013.

WILBURSMITH 2008. Study on traffic and transport strategies and policies in india. *Ministry of Urban Development (MoUD), Government of India.*

WOODCOCK, J., EDWARDS, P., TONNE, C., ARMSTRONG, B. G., ASHIRU, O., BANISTER, D., BEEVERS, S., CHALABI, Z., CHOWDHURY, Z. & COHEN, A. 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: urban land transport. *The Lancet,* 374**,** 1930-1943.

XYNTHE 2012. Property Tax Database for Visakhapatnam. *In:* (GVMC), G. V. M. C. (ed.). Xynthe Technilogies.

YAAKUB, N. & NAPIAH, M. Public bus passenger demographic and travel characteristics a study of public bus passenger profile in Kota Bharu, Kelantan. National Postgraduate Conference (NPC), 2011, 2011. IEEE, 1-6.

YOO, G.-S., KIM, D.-K. & CHON, K. S. 2010. Frequency design in urban transit networks with variable demand: model and algorithm. *KSCE Journal of Civil Engineering,* 14**,** 403-411.

YU, B., YANG, Z. & WANG, L. Design of Frequency of bus line with a bi-level model. Proceedings of the Eastern Asia Society for Transportation Studies The 7th International Conference of Eastern Asia Society for Transportation Studies, 2007, 2007. Eastern Asia Society for Transportation Studies, 218-218.

YU, B., YANG, Z. & YAO, J. 2010. Genetic algorithm for bus frequency optimization. *Journal of Transportation Engineering,* 136**,** 576-583.

ZENINA, N. & BORISOV, A. 2013. Regression analysis for transport trip generation evaluation. *Information Technology and Management Science,* 16**,** 89-94.

ZHOU, J., LAM, W. H. & HEYDECKER, B. G. 2005. The generalized Nash equilibrium model for oligopolistic transit market with elastic demand. *Transportation Research Part B: Methodological,* 39**,** 519-544.

ZIN, T. A., LWIN, K. K. & SEKIMOTO, Y. 2018. Estimation of Originating-Destination Trips in Yangon by Using Big Data Source. *Journal of Disaster Research,* 13**,** 6-13.

LIST OF PUBLICATIONS

Journal articles (published)

Gadepalli, Ravi, Geetam Tiwari, and Nomesh Bolia. 2019. “Operational efficiency of city bus and paratransit systems in developing countries. Case study of Visakhapatnam, India.” *Journal of Advanced Transportation*. (article accepted, in press)

Gadepalli, Ravi, Geetam Tiwari, and Nomes Bolia. 2018. "Role of user's socio-economic and travel characteristics in mode choice between city bus and informal transit services: Lessons from household surveys in Visakhapatnam, India." *Journal of Transport Geography*.

Gadepalli, Ravi. 2016. "Role of Intermediate Public Transport in Indian Cities." *Economic & Political Weekly* no. 51 (9):46-49.

Guttikunda, Sarath K, Rahul Goel, Dinesh Mohan, Geetam Tiwari, and Ravi Gadepalli. 2015. "Particulate and gaseous emissions in two coastal cities—Chennai and Vishakhapatnam, India." *Air Quality, Atmosphere & Health* no. 8 (6):559-572.

Gadepalli, Ravi, Muslihuddin Jahed, K Ramachandra Rao, and Geetam Tiwari. 2014. "Multiple Classification Analysis for Trip Production Models using Household Data: Case study of Patna, India." *Journal of Urban Planning and Development*.

Gadepalli, Ravi, and Geetam Tiwari. 2011. "Evaluating the impact of free left turns on traffic behavior at signalized intersections in heterogeneous traffic conditions." *Journal of the Eastern Asia Society for Transportation Studies* no. 9:1700-1714.

Journal articles (Under review)

Gadepalli, Ravi, Geetam Tiwari, and Nomesh Bolia. 2019. "Integrated and demand responsive transit frequency optimisation in multi-modal transit environments with formal and informal systems." *Public Transport*.

Conference articles (presented)

Gadepalli, Ravi, Geetam Tiwari, and Nomesh Bolia. 2019. Integrated Planning and Frequency Optimisation of bus and paratransit services in Indian cities. In *World Conference on Transport Research (WCTR) Young Researchers Conference*. Mumbai.

Gadepalli, Ravi, and Siddartha Rayaprolu. 2019. Factors affecting performance of urban bus transport systems in India: A Data Envelopment Analysis (DEA) based approach. In *World Conference on Transport Research - WCTR 2019* Mumbai.

Gadepalli, Ravi; Dhok, Divyanka;. 2018. Impact of metro rail systems, service quality improvements and fare changes on bus ridership in Indian cities: Case study of Bangalore. In *Urban Mobility India* Nagpur, India.

Moser, Alex, Ravi Gadepalli, and Martin Fellendorf. 2016. Travel Demand in Emerging Countries: Analysis of Comprehensive Mobility Plans in India In *Transportation Research Board 95th Annual Meeting*. Washington, D. C.

Gadepalli, Ravi. 2012. Traffic Circulation Plans and Street Infrastructure Design for Heritage Areas. Paper read at 13th International Conference on Mobility and Transport for Elderly and Disabled Persons (TRANSED 2012), at New Delhi.

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Education

Ph.D. (2012-2019) - Transportation Engineering, Indian Institute of Technology (IIT)-Delhi, New Delhi

M. Tech (2006-2008) - Transportation Engineering, Indian Institute of Technology (IIT)-Delhi, New Delhi
Thesis: Evaluating the impact of free left turns on signalized intersections

B. E (2002-2006) - Civil Engineering, Andhra University (AU) College of Engineering, AU, Visakhapatnam

Professional Experience

Independent Consultant, Bangalore, India

September, 2017-Current

Key Assignments

- **World Bank**: Working with the World Bank on the project 'Improving Public Transport Services in India' to develop long term public transport strategy, contracting and technology solutions for the states of Andhra Pradesh and Maharashtra
- **UITP India**: Working with UITP-India towards
    - Supporting Bangalore Metropolitan Transport Corporation (BMTC) in developing a transition plan to zero emission buses by 2030
    - Providing inputs to Government of India on incentives to enable electric bus scale up across India
    - Developing a 'Bus Benchmarking' report for Bangalore and Chandigarh cities
    - Recommending 'Financing and regulatory frameworks for shared mobility in India'
- **BMTC**: Supporting **BMTC** on data analytics for service planning, performance evaluation and operations optimisation
- Worked with **Where is my transport**, South Africa on paratransit mapping for Indian cities
- Worked with **Sun Mobility** on 'Deployment plan for battery swap solutions for electric three-wheelers and buses in Visakhapatnam and Bangalore'
- Worked with **ICLEI-South Asia** in developing a 'Low-Carbon action plan for paratransit in Udaipur, India'

- Worked with **German Agency of Technical Cooperation (GIZ) in India** on data management for urban mobility improvements in Indian cities

Shakti Sustainable Energy Foundation (SSEF), New Delhi, India

February, 2014- August, 2017 Program Manager, Transport

Responsibilities

- Developing the transport sector's programmatic engagement strategy that is in line with the latest policy opportunities, emission mitigation potential and donor interest
- Partnering with key National and sub-National Government and Non-Governmental stakeholders to advance partnerships on sustainable transport mandate through a portfolio of grant activities focussed on policy research, technical assistance, capacity building and advocacy

Key projects

Public transport systems

- Roadmap for improving planning, operations and contracting frameworks of city bus systems in India
- Establishing indicators to measure performance efficiency of bus and paratransit operations
- Policy papers on fiscal and regulatory reforms for improved bus based public transport in India

Transport planning and infrastructure design

- Developing urban mobility plans for four 'Smart Cities' supported by Government of India
- Principles for Transit Oriented Development and Land use-Transport Integration in Indian cities
- Planning and design guidelines for the development of bus terminal and depot infrastructure

Vehicular emissions and efficiency

- Policy briefs to support Bharat Stage (BS) VI emission and fuel quality standards, fuel efficiency standards and labelling for Heavy Duty Vehicles (HDV), Light Commercial Vehicles (LCV), Cars and tyres

Freight systems

- Development of trip generation models for urban freight movement in Chennai
- Assessment of vehicle usage characteristics for interstate freight movement in India

- Strategies for increased rail freight share of commodities like containers, cement and automobiles

Transport emissions modelling

- Inter-modal comparisions to prioritise transport sector policies in meeting India's Nationally Determined Contributions (NDC) for Green House Gas (GHG) reduction
- Inputs to city level air quality models to quantify emission reduction potential of transport strategies like modal shift, emission and fuel quality standards, Inspection and Maintenance (I/M) of vehicles etc.

Innovative Transport Solutions (iTrans) Pvt. Ltd., New Delhi, India (June, 2008- Jan, 2014)

Manager, Transportation Engineering: 2012-2014

Team Leader: 2010-2012; Project Engineer: 2008-2010

Responsibilities

- Involved in a wide range of transport planning projects including preparation of Comprehensive Mobility Plans for Cities, feasibility analysis and detailed design of Bus Rapid Transit (BRT) and Non-Motorised Transport (NMT) infrastructure projects, planning for City bus systems in Cities
- Extensive use of modelling and simulation software for travel demand predictions and mode-choice analysis of city road networks, public transport corridors and area level traffic circulation plans

Key Projects

- India' first Low Carbon Mobility Plan (LCMP) for Visakhapatnam
- Multi-Modal Integration plan for Nehru Place Commercial District in Delhi
- Hyderabad Metro station area re-design for improved access for all modes
- Feasibility Study for Bus Rapid Transit System on the East West corridor in Delhi

Software Skills

- Optimization: CPLEX 12.7
- Travel Demand Modelling: TransCAD 6.0, VISUM 12.0, OmniTrans 6.1.1, CUBE 6.0, ArcGIS 10.0
- Others: SPSS 19.0, Biogeme, AutoCAD 2013, VISSIM 5.4, AIMSUN 5.0, HCS 2000

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