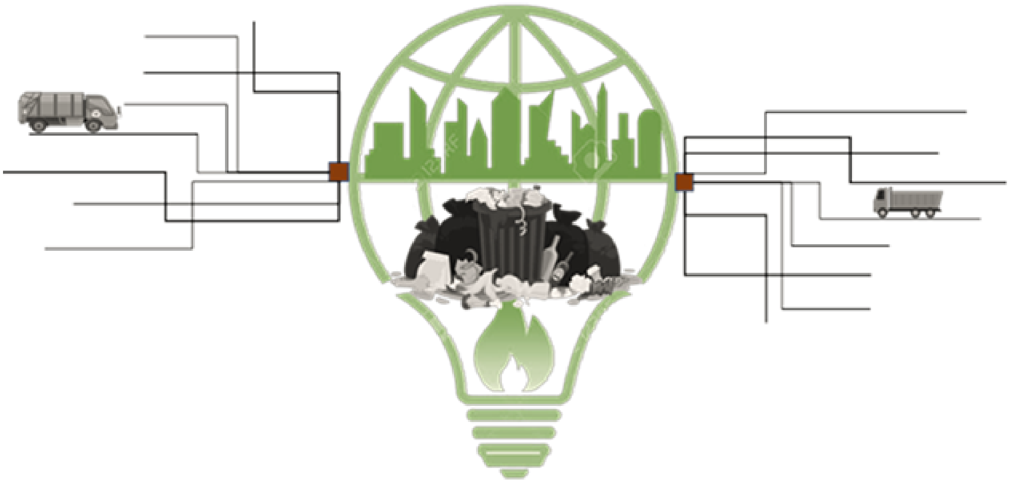

India-UK Joint

Integrated Urban Model for Built Environment Energy Research

(iNUMBER)

Energy Efficiency in Municipal Services: Assessment of City Level Fuel Consumption in Municipal Solid Waste Management

June 2020

R&D Partners - India

CEPT University
Ahmedabad

Indian Institute of Technology-
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India-UK Joint Integrated Urban Model for Built Environment Energy Research (iNUMBER)

Work Package 2 (WP2): Incorporate Municipal Energy Services

Energy Efficiency in Municipal Services: Assessment of City Level Fuel Consumption in Municipal Solid Waste Management

June 2020

Authors:

Sneha Bhattacharyya, Mona Iyer, Sachin S, Rajan Rawal,

Centre for Advanced Research in Building Science and Energy

CEPT University, Ahmedabad

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iNUMBER (iNtegrated Urban Model for Built Environment Energy Research) is a four-year (2017-2021) research project to help cities reduce their energy demand and improve their municipal services. This goal is led by CEPT University, Ahmedabad and supported in India by Indian Institute of Technology Bombay, Mumbai. It is led by University College London, London, and supported by the University of Oxford, Oxford.

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This project would not have been a success without the support of my family and their regular conference calls. Their emotional support and resilience during the global health crisis of Covid-19 Pandemic has kept me sane throughout the project. They deserve a salute and not just gratitude.

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- Sneha Bhattacharyya

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Abbreviations

ADB	Asian Development Bank
BOT	Build-operate-transfer
BEE	Bureau of Energy Efficiency
CAA	Constitutional Amendment Act
DST	Department of Science and Technology
EAP	East Asia and the Pacific
GHG	Green House Gases
GPWM	Global Partnership in Waste Management
GUDC	Gujarat Urban Development Corporation
ISWA	International Solid Waste Association
JNNURM	Jawaharlal Nehru National Urban Rejuvenation Mission
MEEP	Municipal Energy Efficiency Programme
MNRE	Ministry of New and Renewable Energy
MoHUA	Ministry of Housing and Urban Affairs
MRF	Material Recovery Facility
MSW	Municipal Solid Waste
MSWMP	Municipal Solid Waste Management Project (Gujarat)
MuDSM	Municipal Demand Side Management
NAPCC	National Action Plan for Climate Change
NUSP	National Urban Sanitation Policy
PPP	Public Private Partnership
SBM	Swachh Bharat Mission
ULB	Urban Local Body
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UN-HSP	United Nations Human Settlement Programme

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1. Introduction

India, the second most populous country in the world (UN World Population Prospects 2019) is home to over 377 million urban people who live in 7935 towns and cities according to the 2011 census. An estimated 1,50,000 T/day of municipal solid waste is generated in India according to Annual Report of MoHUA in 2016-17, 90% of which was reported to be collected by the urban local bodies. Just like in any other developing countries, in India the cultural notion of “not in my backyard" dominates the perception of the common man regarding solid waste management (Joshi & Ahmed, 2016). With 42.5% of organic content the municipal solid waste in India could pose to be a major GHG emitter if not managed and processed scientifically; especially if the projected generation of 165 million tons per year in the year 2031 is reached (Planning Commission Report 2014). In this context, solid waste management is required to be developed further from a service provision perspective to an economic and ecological service perspective.

Although the nation is equipped with updated rules regarding solid waste management in the Municipal Solid Waste Management Rules 2016, the ground implementation of the rules has not been completely successful in the last 3 years. The Swachh Bharat Mission-Urban along with its daughter program the Garbage Free Cities Program 2018-19 has been fairly efficient in implementing the MSW Management Rules 2016 during its implementation period. As a critical element towards sustainable metropolitan development, municipal solid waste management comprises segregation, storage, collection, relocation, carry-age, processing, and disposal of solid waste to minimize its adverse impact on environment (Joshi & Ahmed, 2016). The mode of energy consumption in each of these phases varies. While the Energy Conservation Act 2001 mandated the formation of the Bureau of Energy Efficiency (BEE) and enabled them to initiate Municipal Demand Side Management of energy, the act only focused on the electrical energy consumption and conservation. It must be noted that a major process within solid waste management, the transportation of waste from point of generation to further processing and disposal consumes a considerable amount of fuel energy. Till date in India transportation of solid waste is dependent on fossil fuel run vehicles and a very slow rate has been observed in the shift towards electric vehicles in urban India; negligible especially in case of municipal utility vehicles (Mohan, Goel, Guttikunda, & Tiwari, 2014).

1.1. Background of iNUMBER Project

This study is a part of the Integrated Urban Model for Built Environment and Energy Research (iNUMBER) which is a collaborative research project between India and United Kingdom aiming to address the topic of “Integration of information, communication and renewable energy technologies at building, community and city level interventions”. This research project comprises of three work packages, out of which the 2nd work package (WP2) focuses on supporting Urban Local Governments in India to understand the energy demands of the cities for various municipal services and then assisting the ULBs in planning and provision of clean and sustainable energy for those municipal services. Ahmedabad has been selected as the primary case city under this work package with an objective to develop a municipal services energy model that can be fed into the City Energy Model. To achieve this objective, existing data sets will be linked with new data sets and developed model will be validated for a range of different scenarios. The Work Package 2 aims at two major outcomes, viz., a 'Feeder for City Energy Model' and a 'Framework for capturing energy consumption in delivering the municipal services'.

Solid Waste Management being an obligatory function and responsibility of the ULB, the energy demand and energy generation potential of this service significantly influences the overall energy demand of a city in providing municipal services. The service of providing efficient municipal solid waste management consist of collection, transportation, treatment and disposal of solid waste which consumes fuel as well as electrical energy. In order to assist an ULB to capture its energy consumption, an outcome targeted by WP2 of the research project, Municipal Solid Waste Management has been considered a major service consuming energy. Hence, the current study of "Assessment of City Level Fuel Consumption in Municipal Solid Waste Management" contributes to the second outcome of the WP2 in the iNUMBER research project.

1.2. Problem Statement

In the 21st century, efficient service delivery in MSW management sector cannot be possible without deployment of motorised transport of these waste in large cities like Ahmedabad. However, the ULBs in India remain oblivious to the fuel consumption among the fleet deployed for such service delivery. This study intends to explore the fuel consumption and factors influencing the same in providing MSW collection services and capture the fuel consumption data that can be fed into the City Energy Model.

1.3. Aim and Objectives of the Study

This research aims to assess the extent of fuel consumption and the fuel efficiency in the process of collection and transportation of waste within the Municipal Solid Waste Management value chain.

To achieve the above-mentioned aim, the following objectives of the study are undertaken:

- Identification of factors which determine the degree of fuel efficiency in the value chain of Municipal Solid Waste Management.
- Establishment of relationship of urban form with fuel consumption.
- Assessment of energy performance criteria within the scope and the extent of availability of reliable data.

- Assessment of the degree of fuel efficiency achieved through the existing fleet in the solid waste collection and transportation in Ahmedabad and potential of further fuel savings within the collection and transportation system.

1.4. Scope and Limitations of the Study

The study focuses on the fuel energy consumed during the collection and transportation phase of the MSW management and the fuel efficiency of the system. The city in focus is Ahmedabad and the study will be carried out within the Ahmedabad Municipal Area. This involves assessment of vehicle performance and factors impacting fuel efficiency. The findings of this study can help the governing body of the city being self-aware of their own energy consumption in providing conservancy services and help them undertake energy audits for the same.

The study is limited to waste collection and transport system and not explore processing and treatment phases as in Indian context much of the processing and treatment is done privately or through informal arrangements and has not been carried out in multiple cities due to low confidence on data reliability. The study is limited to a framework for gathering evidence of energy efficiency and not compare the results of the framework with different scenarios.

1.5. Components of the Study

The study has been executed in two parts. The first part deals with the inventory of fuel consumption data and involves study of urban parameters and relevant units of fuel consumption to use in City Energy Model. The second part of the study deals with identification of fuel consumption as an evaluation criterion for service delivery.

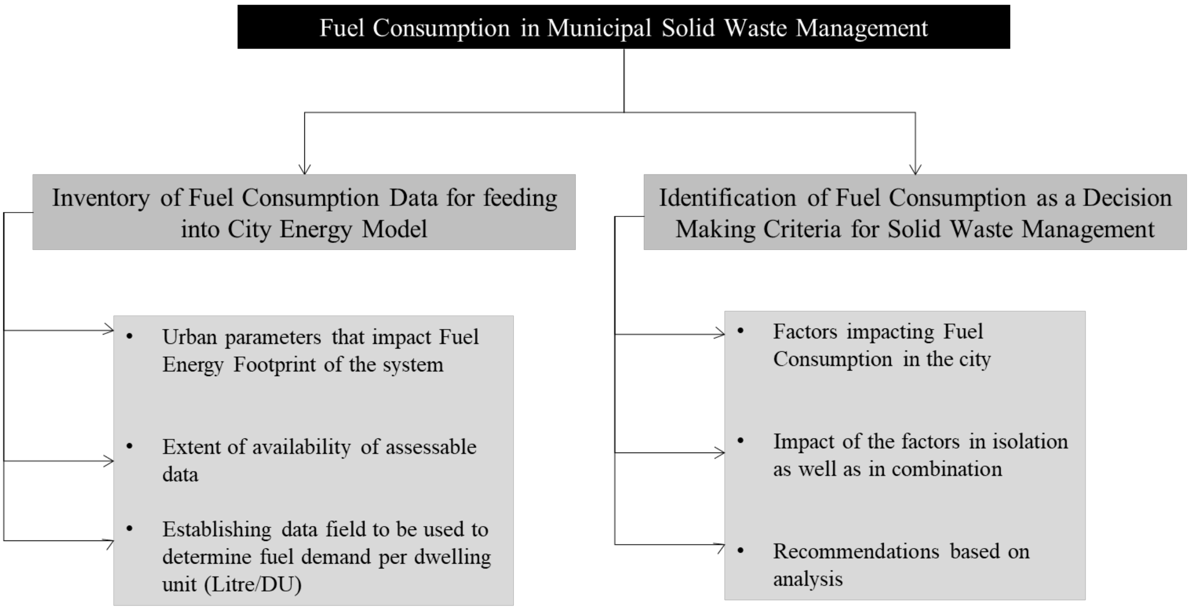


Figure 1: Study is divided into two parts

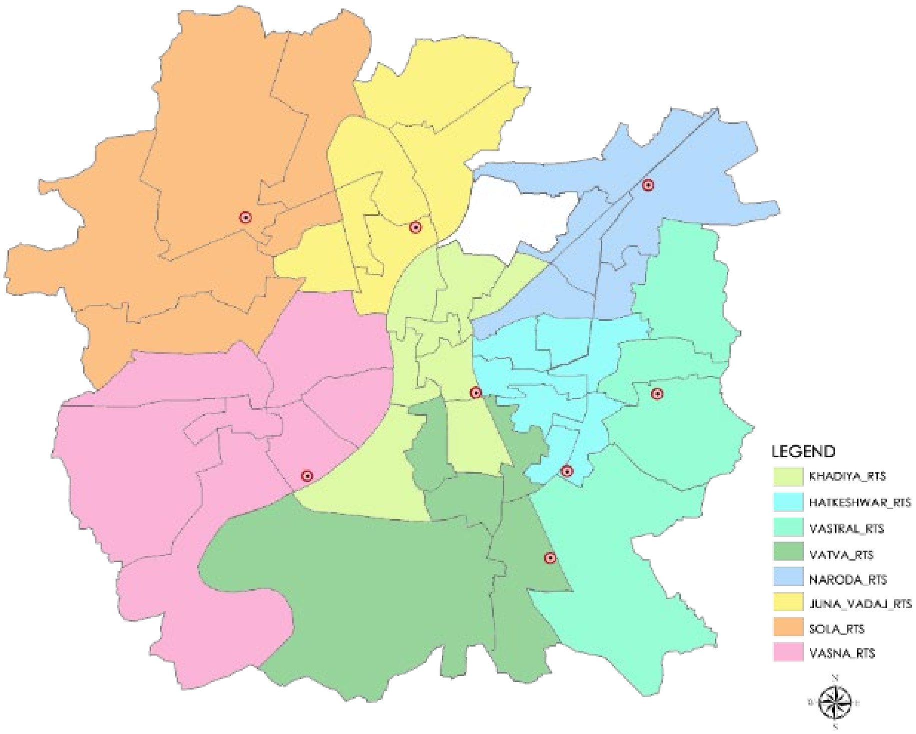


Figure 2: Location of RTS and Wards served by each RTS

2. Methodology

The following methodology has been adopted to carry out the study for achieving the stated objectives:

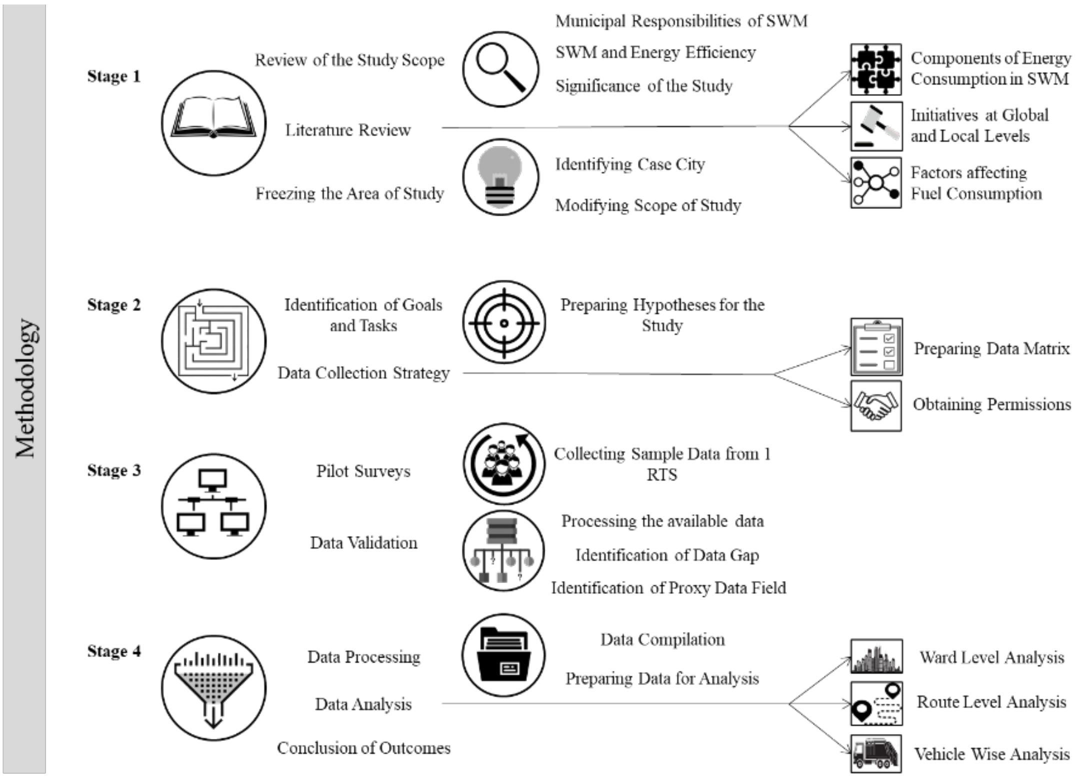


Figure 3: Methodology Stages

2.1. Stages of the Study

The study has been executed in four stages. As shown in Figure 3, the first stage of the study involved review of available literature on the components of solid waste management that contributes to the energy footprint of the service. This stage also involved the review of global and local initiatives that integrate energy parameters to make MSW management more sustainable. Literature on prevalent best practices in tracking energy consumption and recognising potentials of Waste-to-Energy strategies were also reviewed in the process. The first stage was followed by the identification of goals and tasks in the second stage to achieve the study objectives and the data sets required for such tasks. These requirements were listed down in a matrix to further identify the sources of data and the approach required to acquire the data. A strategy involving pilot data collection was formulated in this stage. The third stage involved the pilot survey and data collection of a small sample of 4 wards, compilation of data, identification of data gaps and strategizing the further data collection procedures and the analysis of the available data. This stage also involved the establishment of preliminary relationships among the identified factors influencing fuel efficiency with the fuel efficiency of the sample. In this stage hypothesis was made which further gave a direction for analysis. The fourth stage of the study involved upscaling the data collection to 10 wards, field visits, conducting interviews with officers and staff at Refuse Transfer Station, collection of data, compilation of data and analysis of the data to test the hypothesis.

2.2. Approach of the Study

Pragmatic approach has been adopted in the process of this study. In the first two stages a top-down approach has been adopted where different literature lead us to the identification of study objectives and the required data. The third stage involves a trial and error approach to test the data collection strategies, availability of the required data and the usefulness of the data readily available. The fourth stage involves a bottom-up approach where the final set of available data are used to establish meaningful relationships through observation and data analysis. The final analyses have been triangulated further (Data triangulation) to arrive at a conclusion to the formulated hypothesis.

3. Energy Efficiency in Solid Waste Management

Organised collection and disposal of municipal solid waste has its roots in the late 19th century with the Public Health Act 1875 of London. Hand drawn or horse drawn carts were introduced by the Local Governing Authorities for regular collection, removal and disposal of wastes from kerbside bins (then called "movable receptacles") (as cited in Herbert, 2007, p-11) (Herbert, 2007). The first motored waste transport system was introduced in the 1920 with variety of energy inputs. These included Electric Vehicles, Petrol Powered Vehicles, Steam Traction Vehicles and combination of Horse and Petrol-Powered Vehicles (Herbert, 2007). Since then, with rapid developments in the transportation and motor vehicles industry, the waste collection worldwide steadily shifted from non-fuel carts to fuel powered trucks and compactors. Today the solid waste collection fleets in all the developed countries consist majorly of fossil fuel powered light and heavy vehicles. With such a dependence on fossil fuel in the world to provide solid waste collection services, it has become essential to understand the fuel consumption in the solid waste management services.

Source: New York Times Archives *Source: King County Archives*

Figure 4: Transition from Horse-drawn Garbage Cart to Motorised Garbage Truck

3.1. Solid Waste Management Scenario: Global and Local

After the World War II, the developed countries turned their attention to the development of their cities and the urban economy. In the process many developed countries took up public health and urban refuse management as a priority. This brought the era which shifted the waste collection system from horse drawn carts to motorised trucks since the old army trucks had to be used in some way or the other. The Solid Waste Disposal Act by US Congress in 1965 set in motion the modern system of handling and disposing of municipal solid waste. Soon the issue of solid waste management became an integral part of environment protection worldwide (Hickman, 2003). By the 1980s the waste management policies and solutions worldwide became focused on the elimination of waste through landfilling and incineration activities without any thought to energy consumption or recovery. The scope of recycling and recovery was only realised at the turn of the ultimate decade of 20th century when many European countries revised their solid waste management strategies (Buclet & Godard, 2001). With the Agenda 21 of Rio Summit 1992, Solid Waste Management was recognised as a crucial aspect of Sustainable Development. Currently on the global front, solid waste management forms a key sector for combating climate change through initiatives taken by organisations like UNEP, ISWA and GPWM.

In India, although civic rules preventing nuisance in urban areas were in place since the colonial era, solid waste management remained a neglected part of city administration unlike contemporary European counterparts in the majority of the 20th century. Post-Independence, the policy makers in India passed laws such as Environment Protection Act and several rules under this act to reduce waste and pollution. However, the onus of implementation of these rules were on the local administration of the cities which until the 74th Constitution Amendment Act were not obligated to carry out such implementation. With the formation of 74th Constitution Amendment Act (74th CAA) in 1992, the urban local governments became solely responsible for solid waste management within their jurisdiction. The 74th CAA was followed by the Municipal Solid Waste Rules in 2000 formed as an aftermath of the Surat Plague. These rules laid the procedures to be followed to provide scientific management of waste. The Jawaharlal Nehru National Urban Renewal Mission (JNNURM) launched by the Ministry of Urban Development in the year 2005 provided a platform for the implementation of solid waste management across 62 cities. The mission witnessed a revamp of the waste collection and disposal system where cities started deploying more and more sophisticated waste collection systems with dedicated covered trucks, compactors and GPS fitted vehicles. Subsequently, the municipalities had to ensure lowered carbon footprint and GHG emissions by managing municipal solid waste efficiently under the National Mission for Sustainable Habitat 2011 even if they were excluded from the energy intensive consumer categories in the National Mission for Enhanced Efficiency 2009. The momentum of growth in the sector was achieved finally through the Swachh Bharat Mission (SBM) in 2014 which was directly implemented through the ULBs where all ULBs were mandated to achieve specified standards within the mission period of 5 years. Simultaneously, the National Government amended the existing MSW rules to publish the updated Municipal Solid Waste (Management and Handling) Rules 2016 to aid progress in the initiatives through innovations in technology as well as mandating the extension of solid waste management services to peri-urban and newly urbanized areas outside the jurisdiction of the ULBs. The mission was complemented with a monitoring mechanism through Swachh Survekshan which ranked ULBs on the basis of performance with an additional grading system, the Garbage Free City initiative launched in 2018.

On the other hand, expansion of services meant increasing the fleet of vehicles for solid waste collection which contributes to the fuel requirements of the city. The growing dependency on fossil fuel for transportation in urban areas has long been a concern raised at several world summits. The Global Oil Crisis of 1973 had indicated the limited nature of fossil fuel availability and the subject came under the purview of Climate Change following the 1992 Earth Summit and Energy Conservation was taken up by the UNFCCC in 1997 as a means of combating the climate change. Urban areas worldwide being the highest consumers were encouraged to undergo energy audits by the respective nations. In Europe, the European Commission adopted the EU Action Plan 2015 for circular economy and further integrated it with waste to energy strategy and circular economy in 2017 to align with the 2030 Agenda for Sustainable Development. Many European countries incorporated waste-to-energy strategies under the ongoing Zero Waste Europe policy. India also encouraged its citizens for energy savings and energy rationing through several Institutional Dialogues and Financial Initiatives (Vaish, Iyer, Sachin, Rawal, & Chouhan, 2019). Bureau of Energy Efficiency (BEE) was formed by modification in the already existing Energy Management Centre under the Energy Conservation Act of 2001 by the Ministry of Power. Every energy intensive sector including cities were mandated by the act to undergo energy audits under the direction of the BEE. However, these audits did not include the fuel consumption for cities in any urban sector and focused on electricity conservation instead.

3.2. Perception of Energy Efficiency in Municipal Services

Although there is a robust policy framework for enforcement of energy efficiency at national and state levels, most of the energy efficiency parameters deal with building and industry level energy consumption and generation. Municipal services if considered for energy evaluation under any mission or scheme has exempted the inclusion of Solid Waste Management as a complete process for attaining energy efficiency targets. Integration of energy into solid waste management programmes have been done in a resource recovery perspective through encouragement of material recycling and reduction of new raw materials in the waste stream. However, these programmes do not provide platform for the municipalities to self-assess their energy inputs within the process. Several studies on individual components of the MSW management process reveals there is a potential to integrate energy performance of these components into municipal energy spectrum through assessment of energy consumption and energy generation potential in each stage of the entire process. Fuel consumption in the Solid Waste Collection process which contributes significantly to this municipal energy spectrum has long been overlooked as an essential input. There is a need to consider the fuel consumption in order to develop strategies to achieve energy efficiency in this service.

3.2.1. Fuel as an Energy Parameter in Solid Waste Management

Municipal Solid Waste Management involves a multistage value chain starting with the generation of waste and ending with scientific disposal of residue left after waste processing. These stages are waste generation, waste collection, transportation, waste processing and waste disposal. Among these stages, waste transportation from one facility to other forms a major component involving fuel energy consumption. Waste density, volume and composition determines the type and number of vehicles and number of trips required to serve the area. Location of transfer station and the road layout determines the trip length and speed for each vehicle to travel. These factors of the collection system determine the amount of fuel consumption in the process of waste collection (Coffey & Coad, 2010). Assuming a city to opt for only landfilling as a disposal strategy for the entire waste volume of the city, the fuel consumption in collection and transportation will have maximum contribution to the energy footprint of the solid waste management system. Hence, a systematic study of fuel consumption in the waste collection process is essential for evaluating the energy use in MSW management strategies.

3.2.2. Significance of Fuel Consumption in Solid Waste Collection

For municipal solid waste to be managed in the best possible way, the waste has to be source segregated, removed from the point of generation regularly and transported to such facilities where the waste can be treated and materials and energy can be recovered prior to disposal. This level of service involves a cost which the ULB has to bear by itself from its revenue accounts. The municipal body usually charges the public for the removal of waste from their premises through fixed taxes or charges, large increases in which might become un bearable. Collection and transport of waste hence attracts particular interest as poor optimization leads to high expenditure on fuel on the part of the municipal corporation to keep the system functional.

3.3. Factors Affecting Fuel Efficiency

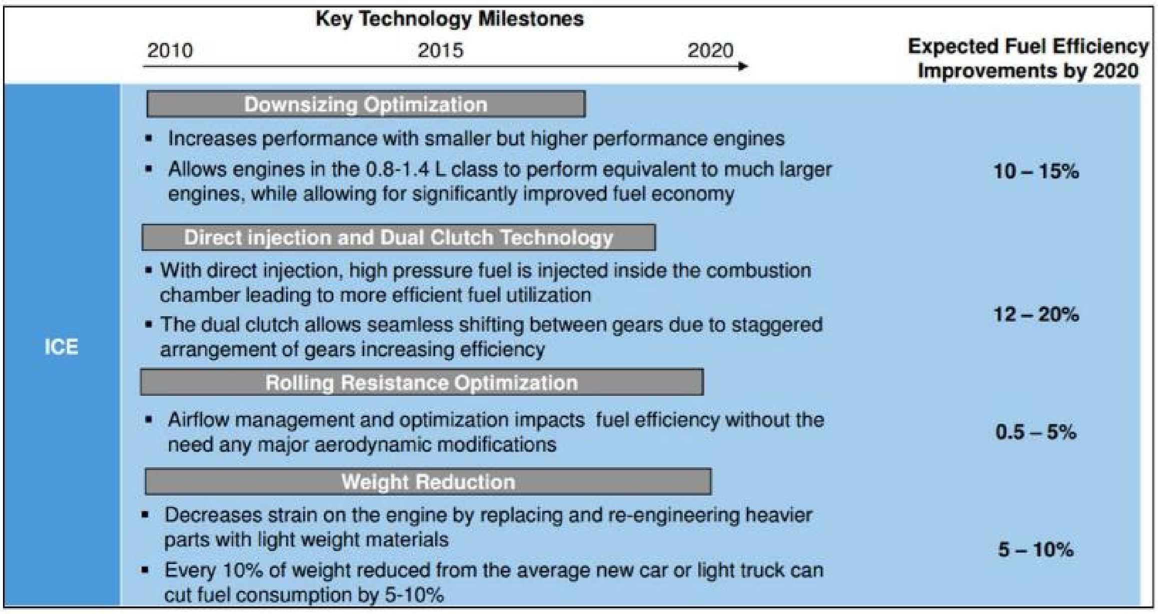
Sustainability in waste collection and transportation system requires efforts to reduce energy consumption. Fuel consumption of vehicles depends on factors like road type, speed, acceleration, road grade, load mass, air conditioning, driving style. An effective tool to assess the extent of fuel consumption in any fleet of transport vehicles is to study the fuel efficiency of the vehicles in the fleet. Fuel efficiency of a vehicle can be defined as the volume of fuel required by the vehicle to transport a unit mass over a unit distance, usually expressed in terms of litre/ton/km or litre/ton/100 km. Studies have found that fuel efficiency of a vehicle varies for different urban settings and drive cycles (Wang, Kelly, Walkowicz, & Duran, 2015) (Ivkovic, Kaplanovic, & Milovanovik, 2017). The fuel consumption in a waste collection system is hence not a function of any isolate factor but a nexus of different combinations of factors. These factors can be categorised according to their nature of influence as Vehicle Specific Factors, Urban Factors and User Specific Factor. Although very less literature is available on the assessment of fuel consumption in solid waste collection, literature available on the fuel efficiency parameters of heavy commercial vehicles and transport buses were referred to understand the complex nature of these factors that influence fuel efficiency.

3.3.1. Vehicle Factors affecting Fuel Efficiency

Factors that fall under this category are essentially the characteristics of the vehicle. These are non-external factors owing to the design and manufacture of the vehicle and will impact on the fuel efficiency of the vehicle in the same way in every given situation. Several literatures (Zacharof, et al., 2016) (Wang, Kelly, Walkowicz, & Duran, 2015) (Ivkovic, Kaplanovic, & Milovanovik, 2017) indicate that the following factors have some degree of impact on fuel consumption and fuel efficiency in case of all kinds of vehicles.

1. **Vehicle Tare Weight:** This refers to the unladen or kerb weight of an empty vehicle. The tare weight of a vehicle is a function of its design or model. A heavy vehicle usually requires more energy to move a certain distance than a lightweight vehicle. In this process, a heavy vehicle will consume more fuel than a light weight vehicle if both vehicles are assigned similar payloads.
2. **Vehicle Payload:** Since it is known that more energy is required to move heavy objects than a lighter one, the same principle applies for payload carried by the vehicles. Two vehicles with similar tare weight will consume different volumes of fuel if the payload they carry are different. The vehicle with lighter payload requires less fuel than the vehicle carrying higher payload.

3. **Vehicle Rolling Resistance:** The tyres of the vehicle along impacts on the fuel consumption since it contributes to the friction with the road surface. This factor is also a function of the road conditions as well as a function of the maintenance of the vehicles. Fuel consumption increases with increase in rolling resistance.
4. **Vehicle Aerodynamic Drag:** The design of the outer structure of the vehicle and its interaction with the air pressure during movement has an impact on the fuel efficiency of the vehicle. A flat frontage of the vehicle will increase the aerodynamic drag and the vehicle will require more energy than a low drag frontage to move over a unit distance at a given speed. This will increase the fuel consumption of the vehicle.
5. **Vehicle Fuel Compatibility:** The fuel type used in the vehicle also has an impact on the economic value of the vehicle although it does not affect the fuel efficiency of the vehicle. The choice of fuel however will impact in the overall energy efficiency of the fleet since a CNG compatible vehicle will consume less fuel per unit distance than a petrol or diesel-powered vehicle and ultimately result in fuel savings.



Source: Booz & Company, 2011

Figure 5: Factors Affecting Fuel Efficiency of Vehicle Engine

3.3.2. Urban Factors affecting Fuel Efficiency

Vehicles consume different volume of fuel to travel a unit distance in different urban conditions. Several urban factors which are essentially non-intrinsic to the vehicles influence this difference in fuel efficiency of the vehicles. Although literature pertaining the waste collection vehicles and their fuel consumption patterns in various urban setting were very less, similar literature pertaining to light and heavy commercial vehicles and trucks have been referred for the purpose of this study. These literatures (Menon & Bandivadekar, 2016) (Ou, Liu, Li, & Chen, 2013) (Marshall, 2008)

(Karathodorou, Graham, & Noland, 2009) have indicated the role of following urban factors in fuel consumption and fuel efficiency of the vehicle fleet.

1. **Distance of Dumpsite/ Landfill/ Transfer Station:** The distance a vehicle has to travel to transport the waste from the point of removal to the point of dump has a direct impact on the fuel consumption by the fleet of vehicle. In case of a centrally positioned dumpsite in the city, the fleet will travel less distance than in the case where dumpsite is located far from the city in the outskirts. In spatially large cities it is advisable to set up multiple point of dump or multiple transfer stations so as to reduce the route length for individual vehicles and save fuel consumption in the fleet.
2. **Route Length:** The number of buildings on a route assigned to a vehicle and the length of road it traverses in order to serve all its assigned service point is called the route of the vehicle. Fuel consumption of a vehicle increases with increase in the route length assigned to it. The route length is again dependent on the built urban fabric along the route. In case of low-rise urban sprawl, the route length increases while it decreases in densely compact high-rise urban core areas.
3. **Urban density:** The density of buildings and dwelling units within a unit special area determines the amount of waste generated in that area and the number of point of services to be assigned to a given waste collection vehicle. Higher the density, lesser the number of buildings served by a vehicle in a single trip. This increase either the number of vehicle or the number of trips made by the same vehicle and eventually increase the fuel consumption by the fleet.
4. **Road Network:** The network of roads and size of urban blocks within a given spatial area also influence the length a vehicle has to travel in order to serve all the assigned buildings. Hence, route optimizations are incorporated while assigning routes to vehicles so that the vehicles travel minimum distance to cover the points of service.
5. **Shape of a city:** A spatially elongated city will require its waste collection vehicles to consume more fuel to transfer waste from the farthest boundaries of the city to the dumpsite/landfill. If a city is monocentric or polycentric, the distribution of the waste collection fleet will influence the total fuel consumption in the city for waste collection.
6. **Traffic Conditions:** Vehicles usually run at very low speed in heavy traffic conditions. Hence, if a waste collection vehicle has to traverse through a high traffic area within its assigned route, it will run at low speed and likely to consume more fuel.

3.3.3. User Factors affecting Fuel Efficiency

The behavioural aspects of the stakeholders that may impact on the performance of a technologically efficient waste collection fleet has also been studied to understand the controllable aspects of fuel consumption in the fleet (McKinnon, 2010) (Coffey & Coad, 2010). The actors in the field of municipal solid waste handling and their role in ensuring fuel efficiency in the system can be enlisted as follows:

1. **Segregation at source:** High degree of segregation of waste at source eliminates the requirement of the intermediate stages like waste segregation stations and material recovery stations. Such approach can to an extent eliminate the requirement of specialised vehicles that can handle mixed waste and transfer them to a central facility. Segregation at source and decentralised disposal of dry recoverable material also reduces the payload of the waste collection vehicle.
2. **Urban Planners:** Planning of the waste collection routes and trip intervals if done in efficient manner ensures least distance travelled while ensuring 100% collection. Also, street layout and urban settlement zoning done at city level impacts the fuel consumption of collection vehicles.
3. **Waste collection staff and Drivers:** Skilled and qualified drivers of waste collection vehicles ensure smooth running of vehicle on road. Case specific planning of collection shifts and collection duration also ensures speedy service delivery and in turn reduces fuel consumption on road. The informal sector comprising of waste pickers who are involved in the parallel recycling market also considerably reduce the load on Municipal solid waste collection services and hence result in high efficiency of collection vehicles. In this scenario, the reduced volume of waste lets a vehicle cover a larger collection route, thus saving fuel.
4. **Maintenance of Vehicles:** Regularly maintained vehicles with advanced fuel-efficient engines perform better than old and worn out vehicles in terms of fuel efficiency. If the fleet consist of new vehicles, the overall fuel efficiency will remain low. With age, the vehicles consume more and more fuel to perform the same amount of work.
5. **Operating Mass:** Vehicles which run beyond their capacity consume more fuel than a vehicle which are utilised at its recommended capacity. Also, if a vehicle runs below its capacity, the fuel efficiency reduces due to the low mass carried over the distance at a given fuel consumption.

4. Data Collection and Analysis

The study of available literature has led to the identification of quantifiable variates that influence energy consumption. While the framework of a policy or mission and the programmes undertaken under those policy provide opportunities to adopt new technologies, it is the responsibility of the planning agency and service providers to select those technologies that ensure least energy consumption. The vehicles procured for the collection service should conform to latest standards for ensuring energy savings.

Energy consumption in the collection and transportation stage of solid waste management value chain is a function of not only the technical specifications of the compactor equipment and vehicles, but also a function of skill of the stakeholder involved in the management process. Urban morphology parameters like population density and land-use of a locality hugely determines the amount of waste generated and in turn governs the trip frequency of a vehicle. Availability of a waste transfer station can reduce the fuel consumption owing to reduced trip length to be covered by primary collection vehicles. Trip lengths coupled with number of trips and the carrying capacity of a particular vehicle impact its fuel consumption.

Analysis of a large sample across all the functioning refuse transfer station within the city will provide the total fuel requirement of the city for ensuring efficient conservancy services. For the purpose of such an analysis, a detailed data requirement matrix was prepared to take forward the field surveys and data collection for the study.

For the study, primary and secondary data has been collected from various sources. The Analysis parameters that were identified from the literature reviews led to the formation of an initial data collection strategy. A set of pilot surveys were carried out to validate the availability of required data prior to collection of entire data. The final data was then collected through surveys, interactions with officials and access to computerised database with the Municipal Corporation. Data has been collected for 12 wards out of which complete data sets for 10 wards could be prepared for further analysis.

4.1. Data Collection Methodology

Data has been collected in 2 phases involving a trial and error approach in the first phase and purposive convenience-based approach in the second phase.

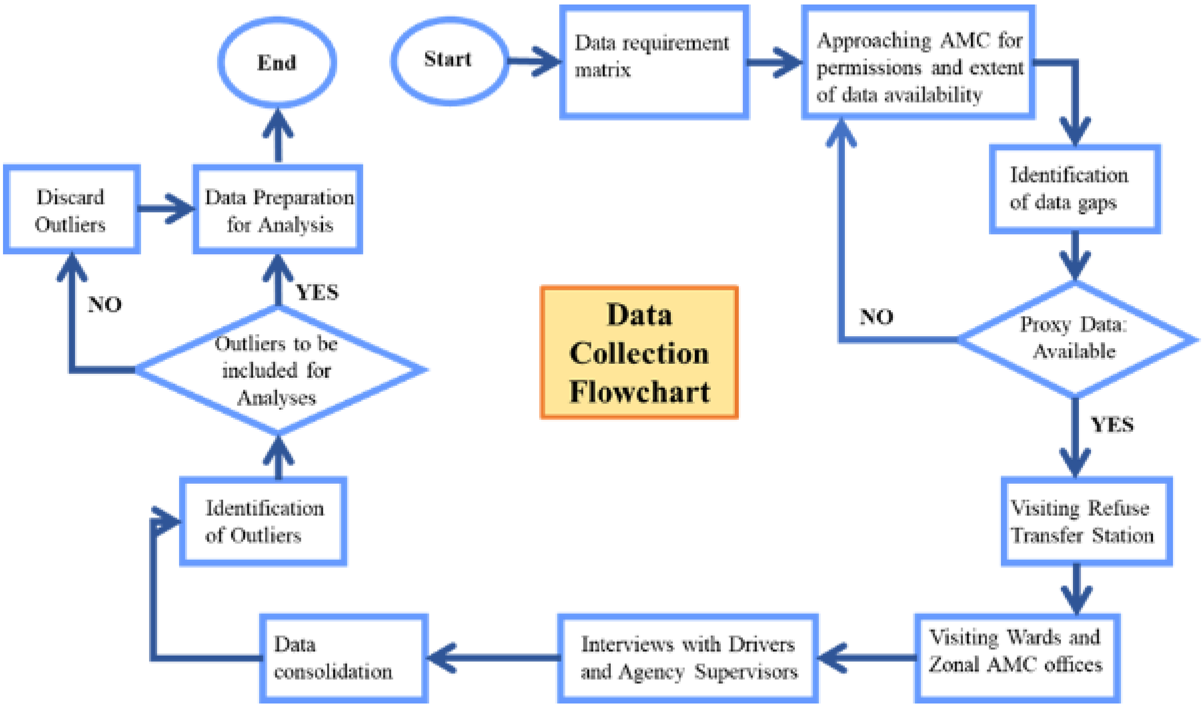


Figure 6: Data Collection Flow Chart

At first, the data required for meeting the stated objectives of the study along with the possible sources of the data were enlisted in the form of a Data Matrix based on the extensive literature review on similar studies carried out across the world. The Ahmedabad Municipal Corporation was consulted and permissions were taken to collect the required data from their own and allied databases. Pilot surveys were conducted at the Juna Vadaj RTS and the wards under its service to identify the data gaps and proxy data for such data gaps. The Municipal Corporation was approached for consultation regarding data gaps for which proxy data could not be identified. The Data Matrix was updated and the second phase of data collection was carried out. In the second phase, 2 zones with 6 wards each were selected for survey on the basis of Purposive Sampling and Cluster Sampling, viz., West Zone (Nava Vadaj RTS) and Central Zone (Khadiya RTS) as these zones were roughly representative of the whole city in terms of land-use and built fabric. In case of each zone, the transfer station (RTS) were the first point of approach in order to collect weighbridge record, vehicle ownership data and vehicle refuelling log from contracted private agency supervisors. The second point of approach were the AMC Zonal Offices and Ward Offices for collection of route distribution data and route maps. Interviews were conducted with private agency supervisors, drivers and waste collection staff of sample routes.

4.2. Data Requirements

A data requirement matrix was prepared which includes the type of data, Key official to approach for the data, desired format of the data, desired granularity and alternative/proxy data. A Pilot Survey of Juna Vadaj RTS (West Zone) was carried out to test the availability of the required data. Data gaps were identified and proxy data field were decided as shown in Table 1. Simultaneously, a structure for analysis was prepared that could use the available data.

Table 1: Data Requirement Matrix

Data Required	Data Source	Availability	Proxy Data	Status of Collection
Ward wise distribution of waste collection vehicles	AMC Zonal Office	□	—	Collected and Compiled
Load carrying capacity of each vehicle	RTS	□	—	Collected and Compiled
Aerodynamic Drag and Rolling Resistance	—	□	Not Available for specific vehicle model	Not Collected
Waste collection by each vehicle per trip	RTS- Weighbridge Records	□	—	Collected and Compiled
No. of trips per vehicle	RTS- Weighbridge Records	□	—	Collected and Compiled
Route length assigned to each vehicle	AMC Ward Offices- Ecoskipper	□	—	Collected and Compiled
Route characteristics for each vehicle	GIS map- Secondary Data from CEPT	□	—	Collected and Compiled
Distance of assigned route from RTS	AMC Ward Offices- Ecoskipper	□	—	Collected and Compiled
Total travel length of each vehicle	Agency Supervisors- Refueling Log	□	—	Collected and Compiled
Daily fuel consumption of each vehicle	Agency Supervisors- Refueling Log	□	—	Collected and Compiled
On duty running speed of vehicles	—	□	Daily duration of service divided by total travel length	Collected and Compiled
Vehicle condition	Agency Supervisors	□	Not Available for specific vehicle model	Not Collected
Ward Size	GIS map- Secondary Data from CEPT	□	—	Collected and Compiled
Population of wards	Secondary Data from Literature	□	—	Collected and Compiled
Traffic Condition on the Routes	—	□	Right of Way of the routes assuming traffic condition to be same	Collected and Compiled
Road characteristics of wards	—	□	Right of Way of the routes	Collected and Compiled
Road Surface Condition	—	□	Not Available for the routes	Not Collected
Building typology along each route	GIS map- Secondary Data from CEPT	□	—	Collected and Compiled

4.2.1. Data Source

Data sets on the incoming waste volume per trip per vehicle, vehicle characteristics, ownership and vehicle distribution were obtained from the weigh-bridge records of the RTS in each zone. The daily travel length and fuel consumption for each vehicle were obtained from the daily refuelling logs present with the private agency supervisors responsible for the upkeep of the separate fleet. Route of each vehicle was obtained from Sanitary Sub Inspectors (SSI) in each ward by accessing the Ecoskipper application. The application also provided the number of properties/ points of service assigned to each vehicle. Data on ward characteristics and decision-making criteria for vehicle distribution was also obtained through interactions with the SSI. Data on built fabric, built density and urban form of the wards were obtained in the form of GIS maps from the database prepared by the Understanding the City Studio 2019 of CEPT University.

The data collected from the above sources formed a raw data which needed to be triangulated and compiled to exclude data repetition and identify outliers which may skew the analyses of the study.

4.3. Data Compilation

Preliminary data consolidation was done to identify outliers if any within the data to be used for analysis. The outliers were verified through interviews with Sanitary Inspectors and vehicle drivers. Sample routes were identified for analysing the factors affecting fuel consumption in the context of Ahmedabad.

4.3.1. Data Gap Identification

Through the process of data compilation several data gaps were identified. These data are not available with the Solid Waste Management Department of Ahmedabad as no system exists to capture these data for further utilisation. Such data were:

- Age of Vehicles: The Agency Supervisors are not aware of the exact age of vehicles although they have records of procurement of vehicles. It is highly possible for a few vehicles to be procured in already old condition.
- Fluctuation in speed of vehicles during duty hours.
- Duration of completion of each trip for each vehicle.
- Traffic conditions on the routes during vehicle duty hours.
- Aerodynamic drag and rolling resistance of vehicles.
- Street surface conditions.

4.3.2. Proxy Data Identification

Due to unavoidable circumstances, the identified gaps in the data set could not be filled during the course of the study. This has prompted the inclusion of proxy data sets for the purpose of establishing certain relationships within the scope of the study. Such proxy data sets can be listed as follows:

- Proxy data for Speed: The daily total duration of service of each vehicle was considered to calculate the average speed of the vehicle during collection of waste.
- Proxy data for Trip-wise Duration: The daily total duration of service was divided by number of trips to get an approximate value of duration.

- Proxy data for Traffic Conditions: The Right of Way of the routes assigned to vehicles have been considered as a proxy data. Also, the traffic flow has been assumed to be same across the city.

4.3.3. Data Preparation for Analysis

The data on route length, number of trips per route and distance of the service area from the RTS were triangulated to generate expected travel length for each vehicle. The expected travel length was validated against the actual daily travel length to identify anomalous data points that may affect analyses. Anomalous data points were excluded from the final data set for analyses. Similarly, the outliers were excluded from the final data set for analyses.

4.4. Data Analysis Methodology

The study has been split into two parts as follows:

- Creation of an Inventory of Fuel Consumption Data for feeding into City Energy Model.
- Identification of Fuel Consumption as a Decision-Making Criteria for Solid Waste Management.

For the first part of the study, the total fuel consumption of each of the two RTS was calculated. The fuel consumption data for 12 wards were calculated from vehicle re-fuelling data available for each vehicle category. This has been done in a matrix where further data from new wards can be fed. Door-to-door routes were taken into consideration for finding a unit value for fuel consumption (Litre/D.U. or Property). The routes were classified into categories based on the predominant building typology (building height) along the route. For each predominant building height, average waste collection, average number of dwelling units and average fuel consumption (based on proximity to RTS) were calculated.

For the second part of the study, the fuel consumption for vehicles categories were correlated with the following factors impacting fuel consumption in a ward:

- Vehicle fuel efficiency
- Vehicle Operating Efficiency
- Distance of Service Area from RTS
- Total Travel Distance covered daily
- No. of Vehicles deployed

Correlation and regression analyses was carried out to establish the degree of relationship between the fuel consumption and individual factors. For regression, fuel consumption has been taken as a dependent variable. Factors showing strong correlation will be further verified in the next stage of the study where the analyses will be expanded to pan city.

4.4.1. Case Studies

In order to carry out data analysis to achieve the objectives of the study, previous researches similar to this study were referred as literature to understand the inter-relations between the data sets and the statistical tools of analysis that can be utilised to establish any relationship among the data. The following case studies from literature has helped in developing the analysis framework of this study:

- "Quantifying the Relationship Between Urban Forms and Carbon Emissions Using Panel Data Analysis" – (Ou, Liu, Li, & Chen, 2013)– (Springer Journal): In this study, 4 cities with different growth patterns and urban land-use have been compared on the basis of the influence of City Shape, Number of Urban Cores, Land use and Road Network on the carbon emissions of the cities.
- "Estimating the effect of urban density on fuel demand" – (Karathodorou, Graham, & Noland, 2009) – Imperial College London (Elsevier Journal): The study has considered fuel consumption per capita as the product of car ownership per capita, fuel consumption per km and annual distance driven per car. 100 cities were compared on the basis of urban density and coefficient of correlation with various significance value were obtained.
- "Influence of Road and Traffic Conditions on Fuel Consumption and Fuel Cost for Different Bus Technologies" – (Ivkovic, Kaplanovic, & Milovanovik, 2017) – University of Belgrade: In this study 3 different bus technologies were compared with each other on the basis of Fuel Consumption. Operating speed, fluctuation of traffic volume, and correction factors were selected as indicators of traffic conditions that influence Fuel Consumption. Terrain type (flat, hilly, mountainous), international roughness index (IRI) were selected as indicators of Road conditions that influence Fuel Consumption. Simulation of total fuel consumption and fuel savings in each scenario has been explored – present fleet, increased fleet (+20%), decreased fleet (-20%)
- "Quantitative Effects of Vehicle Parameters on Fuel Consumption for Heavy-Duty Vehicle" – (Wang, Kelly, Walkowicz, & Duran, 2015) – SAE International: The study was done for 3 types of drive cycles on the parameters of vehicle weight, aerodynamic drag and vehicle rolling resistance and their influence on fuel consumption by the vehicles. Simulations of these factors (increasing 5% or decreasing 5%) were explored to study the fuel consumption in each scenario.
- "Review of In Use Factors Affecting the Fuel Consumption and CO2 Emissions of Passenger Cars" – (Zacharof, et al., 2016) – European Union: A sample of different vehicles in the European Fleet including private cars and LCVs were analysed and compared for their Fuel consumption and CO2 Emissions. Various use factors were considered for this study which includes Auxiliary system, Driving Behaviour, Occupancy, Vehicle Maintenance Condition, Operating Mass, Traffic condition, Speed, Environment and Choice of Fuel.

4.4.2. Analysis Tools used in the Study

The tools of analyses used in this study include both quantitative and qualitative analyses. These involve statistical correlation and regression on directly dependant factors of fuel consumption with actual fuel consumption. Correlation has been used to determine the presence and strength of any relationship of the factors. Regression has been used to establish a possible relationship equation between the variables. Quantitative analyses include determining relationship between measurable parameters like volume of waste, mass of load carried, travel length on fuel consumption and qualitative analyses include determining the effects of land use, shape of wards, urban form and route characteristics on fuel consumption.

5. Fuel Efficiency in SWM in Ahmedabad

Ahmedabad is a fast-growing metropolitan city in India with a population of 5.6 million and a decadal growth rate of 14% according to 2011 Census. The radio-centric city has been estimated to house a population of 8.3 million by the year 2031. Being a historical centre of trade and commerce, the city can be identified by its textile industry, pharmaceutical and chemical industry and premier educational institutions. With a rapid urbanisation and growth, the city manages its day-to-day functioning efficiently under the Ahmedabad Municipal Corporation (AMC) which governs 466 sq.km of the city. The municipal corporation (AMC) by the mandate of 74th CAA is responsible to keep the city clean. For this purpose, the AMC has a dedicated directorate of Solid Waste Management which handles the entire solid waste sector of the city.

The system of solid waste management in place within the boundaries of AMC involves a multi-level strategic operation guided by the Solid Waste (Management & Handling) Rules 2016. Out of the 4000 Metric Tons of solid waste collected and transported from the city, nearly 50% comes from municipal bins and from street sweeping. Since July 2009, the AMC has consistently provided Door-to-Door collection services for all days of the year. The collection of waste starts from 7.00 am onwards and covers more than 1400,000 Points of Service daily. The vehicles dedicated to the Door-to-Door collection are regularly tracked and mapped through GPS using the Ecoskipper Application by Infinium. Approximately 1000 TPD of waste is collected from 750 waste collection spots by Spot-to-RTS tippers and Compactor vehicles. The Spot-to-RTS tippers collect solid wastes from designated nuisance spots which were earlier dedicated for community bins. The community bins were withdrawn from service with the introduction of Bin-Free City program in 2018 which has given rise to such open dumping spots. The Silver Bin compactors collect waste from the 1-ton silver bins kept at kerbside which are dedicated for street sweeping refuse and local community garbage disposal. In the central zone the silver bins have been withdrawn and nuisance compactors have been deployed to collect community and street sweeping wastes directly from the street sweepers. Collection, transportation and composting of kitchen and biodegradable waste from hotels and restaurants have been outsourced to different agencies.

Figure 7: Ecoskipper Route Replay Page

Waste collected from individual points of service are transferred to the 8 Refuse Transfer Stations (RTS) across the city where the accumulated waste is further compacted and loaded into large containers and Hook-loaders of 20 - 25 CMT Capacity which can carry 10 to 12 MT of MSW. These containers and hook loaders transfer the waste to the Pirana Dumpsite for further treatment and disposal. Informal Material Recovery is also done at the RTS apart from the dedicated 70 Metric Ton capacity fully automated MRF plant by NEPRA (SWM Department, AMC).

Figure 8: Waste Compaction and loading Hook Loader at RTS

Figure 9: Informal Material Recovery by Sakhi Mandal at RTS

The complete system of waste collection is contracted to various private agencies who serve specific wards with their fleet. Fuel requirements in these vehicles are hence not under the direct supervision of the Municipal Corporation but rather a responsibility of the agency supervisors. This leads to a lack of centralised database regarding fuel consumption of each vehicle unlike the route length distribution which can be centrally accessed through tracking applications. Hence there exists a deficiency in monitoring the fuel expenses for collection and transportation by vehicles.

Vehicle Distribution across Municipal Wards:

Out of the 8 RTS, vehicle data from the Juna Vadaj RTS and the Khadiya RTS has been analysed. Both the RTS deploy a variety of vehicles which can be grouped according to their capacity and purpose. These vehicles are:

- 1 Ton Capacity Door-to-Door Vehicles
- 2 Ton Capacity Door-to-Door Vehicles
- 2 Ton Capacity Spot-to-RTS Vehicles
- 7 Ton capacity Nuisance Compactors
- 7 Ton capacity Silver Bin Hoppers
- 12 Ton capacity Hook Loader (RTS-to-Pirana)

Figure 10: Waste Collection Vehicles (L-R: 1-ton D-to-D, 2-ton D-to-D, 2-ton Spot-to-RTS)

Figure 11: Waste Collection Vehicles (L-R: Silver Bin Hopper, Nuisance Compactors)

The RTS considered for the study serves 6 wards each. The waste collection vehicles are distributed among the wards such that each vehicle can cover a fixed number of service points on a specific optimum route.

5.1. Inventory of Fuel Consumption in MSW Collection

In this section of the study, the relationship of urban characteristics with the fuel consumption in different wards of Ahmedabad has been studied. In this process, the land-use, shape of wards, demography, predominant building heights, density of development and route characteristics were compared across the wards in order to determine the type of relationships between these factors and their effect on fuel consumption.

The fuel consumption of the 12 sample wards were used as a basis to estimate the overall fuel consumption in the city in the MSW collection services. Such an estimate provides the fuel consumption rate of the city as well as separate ward in terms of per capita, per sq.km of city area, per sq. m. of urban floor space, per running km of route and per Ton of waste. The fuel consumption rate can be used as a unit to be fed into the City Energy Model which will help in understanding the overall energy footprint of the entire city.

5.1.1. Relationship of Urban Form and Waste Collection Routes

Urban Form can be defined as the physical form of an urban area which includes the spatial dimensions, shape, size and the configuration of the urban are or its parts. Characteristics of the urban form range from building typology at local scale to street layout, cluster of settlements, land-use and spatial arrangement or layout at wider city scale. Waste generation and collection varies with different socio-economic spatial arrangements in the city which can be reflected in the route optimisation for waste collection systems and its implications on fuel consumption. It has been assumed that the spatial area of a ward has an influence on the decision route optimisation in that ward. Such a hypothesis has been earlier demonstrated by Ou, Liu, Li and Chen (2013) for quantifying relationship between urban forms and carbon emissions in the cities of Beijing, Shanghai, Tianjin, and Guangzhou. In our study, a similar relationship was attempted for studying the Fuel Consumption with respect to the Urban Form of Wards. In this section of the study, the wards have been categorised according to their shapes and relationship of their land-use and population density with length of waste displacement and fuel consumption has been compared.

The wards were categorised in the following way:

- **Monocentric Wards:** These wards have a single prominent centre of activity where either the streets converge or around which neighbourhoods align. Wards with no prominent centre of having a homogenous characteristic can also be categorised as monocentric.
- **Elongated Monocentric Ward:** These wards are similar to monocentric wards with a single prominent centre but have a linear spatial arrangement.
- **Bicentric Wards:** These wards have two separate urban centres which may be completely different from one another. For example, in case of Ranip, the southern part of the ward has a dense residential arrangement around the Shak Market and the northern part is arranged in a scattered development with an industrial strip forming a centre of activity.
- **Polycentric and Elongated Polycentric Wards:** These wards have multiple divisions with specific development characteristics. Each of these divisions may have a separate centre of activity.
- **Polar Wards:** These wards are similar to the monocentric wards but their centre of activity is situated at a corner of the ward. In such wards, the street layout radiates from the activity centre and hence requires all the waste collection routes in the ward to begin or end at a common location.

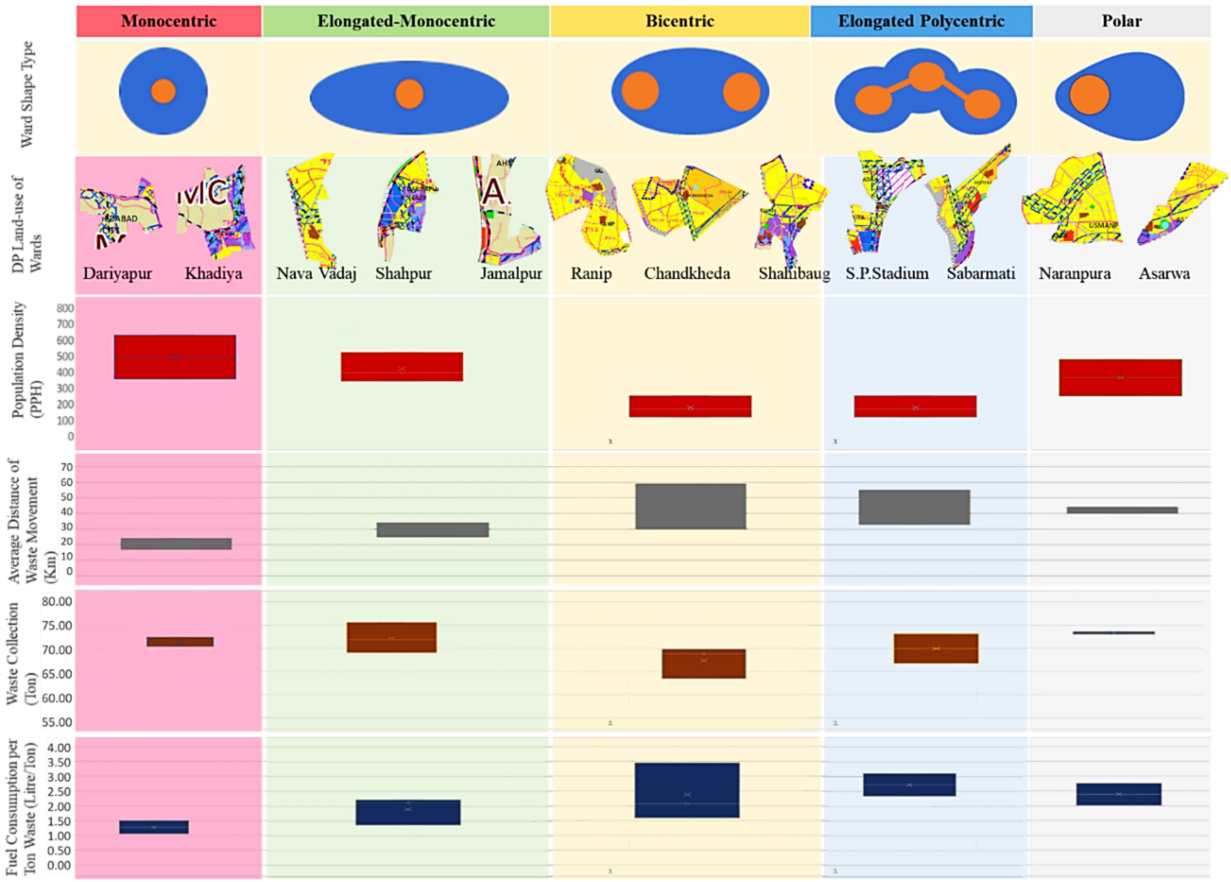


Figure 12: Comparison of Urban Form and Fuel Consumption across Wards

Fuel consumption in a ward in the context of MSW collection depends on the distance a vehicle has to travel to collect the waste. In an urban area, several urban characteristics contribute to the travel length.

The monocentric wards among the 12 sample wards under study is located in the walled city of Ahmedabad which is characterised by the highest population density in the city. Comparing the population density ranges for each shape category, it can be observed that the population density in bicentric and polycentric wards are very low unlike wards in monocentric, elongated monocentric and polar wards. This might have resulted in the range of distance for waste movement from ward to dump. Monocentric wards like Khadiya and Dariyapur have high population density and subsequently the average distance of waste displacement remains low.

The waste collection pattern mimics the population density in each category to some extent as evident from the low minimums in the bicentric and elongated polycentric categories than other type of wards. This variable is not dependent on the ward shape but rather dependent upon the resident population and the land-use of the wards. Low population density in wards with large chunks of residential area implies scattered development unlike the dense developments in high density wards. This leads to longer routes for removing a given quantity of waste from the wards to the RTS. This is evident from the wide range of average distance of waste movement for Bicentric and Elongated Polycentric ward categories in Figure 12. The shape of the ward comes in the context of the distance of displacement. It can be observed that wards with single prominent centre of activity such as monocentric and polar wards have shorter variation in distance of waste displacement within the respective category. A probable reason for such a phenomenon can be the uniform arrangement of routes in such wards.

It can hence be established that if a residential bicentric or polycentric ward has very low population density and exhibits scattered built fabric, the average distance of waste displacement will increase and subsequently, the ward will have high fuel consumption for MSW collection.

5.1.2. Relationship of Ward Characteristics on Waste Collection

For the purpose of studying the fuel efficiency in the waste collection and transportation, it was essential to understand the collection pattern of the waste in each ward. According to Ahmedabad Municipal Corporation the city generates 3800 Metric ton of MSW daily which translates to approximately 0.6 kg per capita per day. However, the collection of a large chunk of waste that comprises C&D waste, Restaurant Kitchen waste and Animal Carcass do not come under the purview of the RTS system of waste transfer. Hence, if waste generation is estimated for the 12 wards under study taking the 0.6kg per capita value, it is supposed to be higher than actual waste collection in the wards.

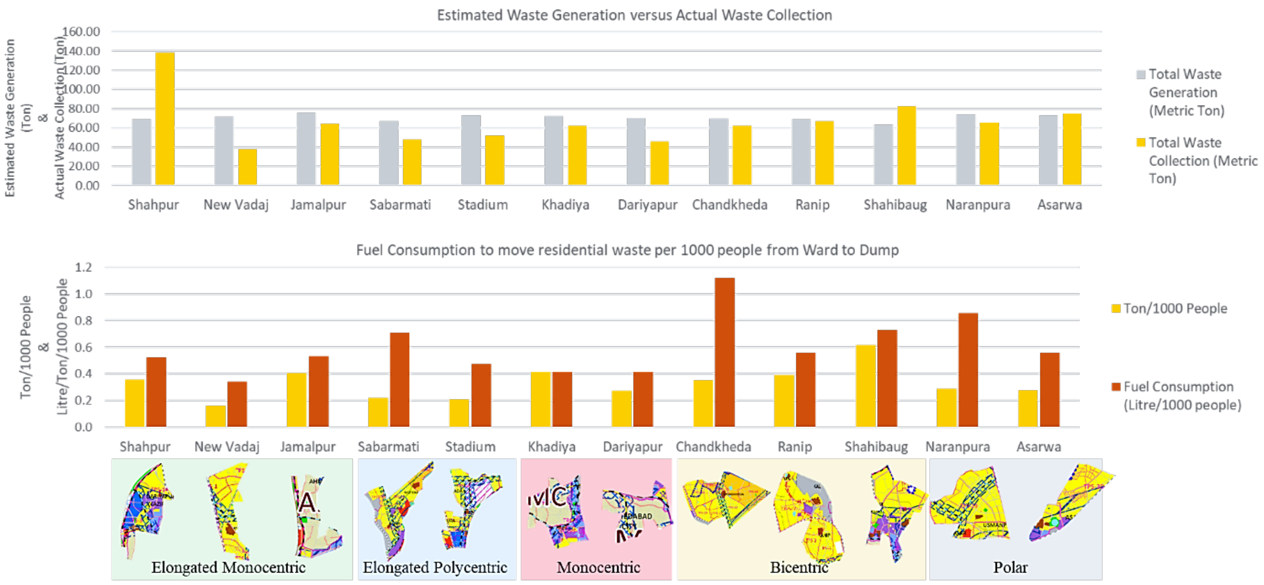


Figure 13: Comparison of Waste Collection across Wards based on land-use

It has been observed that although the estimated waste generation is higher than the actual waste collection in most of the wards, Shahpur, Shahibaug and Asarwa stand as outliers which might be due to the presence of commercial and industrial activities in the wards.

However, when the residential Door-to-Door waste collection was studied across the wards, Shahpur does not exhibit unexpectedly high collection. However, Shahibaug stands out in the comparison with

0.62 ton/1000 people daily (translates to more than 0.6 Kg/capita/day). Such a scenario might be a result of affluence in the resident population or commercial and industrial refuse entering the MSW stream during residential waste collection.

The residential waste collection has been studied along with the fuel consumption in the process. For this purpose, fuel data of only Door-to-Door vehicles were considered. As evident in Figure 13, Chandkheda, Sabarmati, and Naranpura exhibit very high fuel consumption compared to the waste volume per 1000 people. Since it has been already established previously that Chandkheda and Sabarmati have low population density and scattered residential developments, the high fuel consumption can be attributed to longer routes in these wards. However, for Naranpura ward which has a moderate population density of 250, the high fuel consumption can be contributed by several other factors like vehicle distribution in the ward, urban configuration within the ward or the location of the wards with respect to the RTS.

5.1.3. Relationship of Fuel Consumption and Vehicle Distribution

To verify the high fuel consumption in Chandkheda, Sabarmati and Naranpura for residential waste collection per 1000 people, the fuel consumption rate per 100km in every ward has been studied with the average distance of waste movement. Also, the distribution of vehicles in the wards and their corresponding fuel consumption has been studied. It has been assumed that the distribution of vehicles in a ward is a factor contributing to the total fuel consumption in the wards.

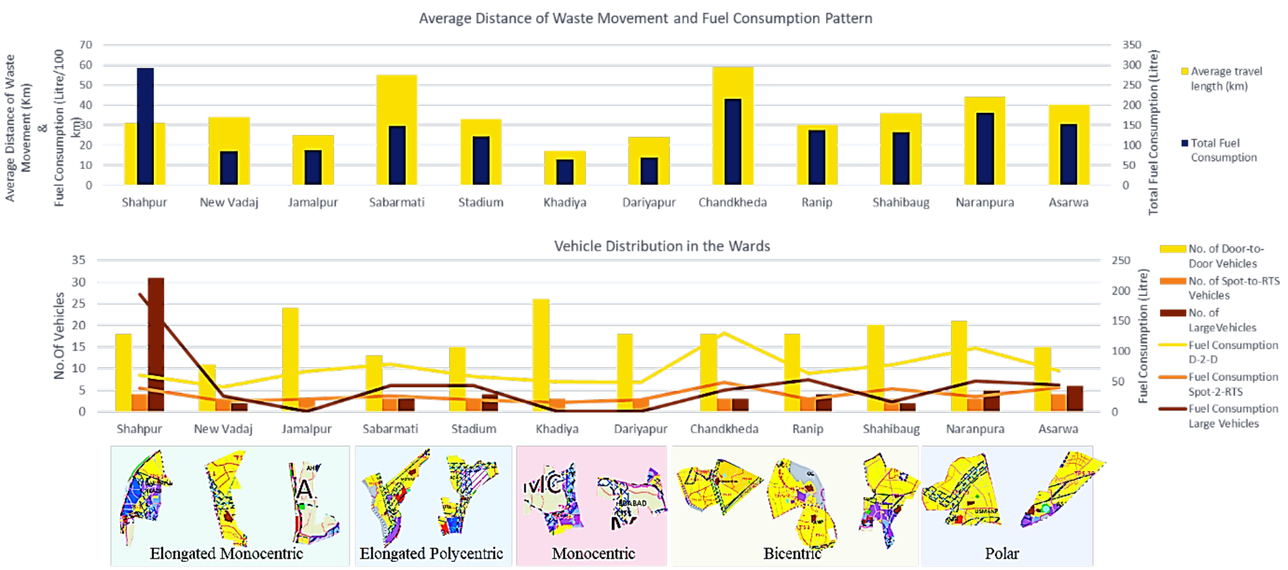


Figure 14: Fuel Consumption and Vehicle Distribution across Wards

It is a known fact that increase in distance leads to increase in fuel consumption. The graphs in Figure 14 explains to an extent the high fuel consumption per 1000 people in Chandkheda and Naranpura. Both the wards have longer distance of waste movement than other wards. However, it might be noted that Shahpur falls as an outlier as it exhibits highest fuel consumption although the average distance of waste movement is low. The high fuel consumption in Shahpur can be explained by the number of compactor vehicles deployed in that ward. Here a few wards exhibit low fuel consumption in the Door-to-Door Vehicle category in spite of deploying more vehicles. These wards are situated near the RTS and hence have short distance of waste movement. Similar observations can be made in case of Chandkheda and Naranpura where the fuel consumption in Door-to-Door vehicles spike up which might be explained by their location with respect to the RTS.

5.1.4. Impact of Route Characteristic on Fuel Consumption

Since it has been observed that fuel consumption reflects the total travel length for waste collection and transportation, the two variables were studied in the context of different types of vehicles deployed for waste collection. The correlation coefficient between travel length and fuel consumption for 1-ton, 2-ton and 7-ton capacity vehicles were 0.95, 0.96 and 0.97 respectively. This implies an obvious dependency of fuel consumption on the distance travelled by the vehicles. The fuel in a vehicle is consumed to move the vehicle over a distance which means that more a vehicle travels, more fuel it consumes. In case of municipal solid waste collection, the theory holds true and a collection vehicle traveling longer distance to collect waste will consume higher volumes of fuel than a vehicle traveling short distances.

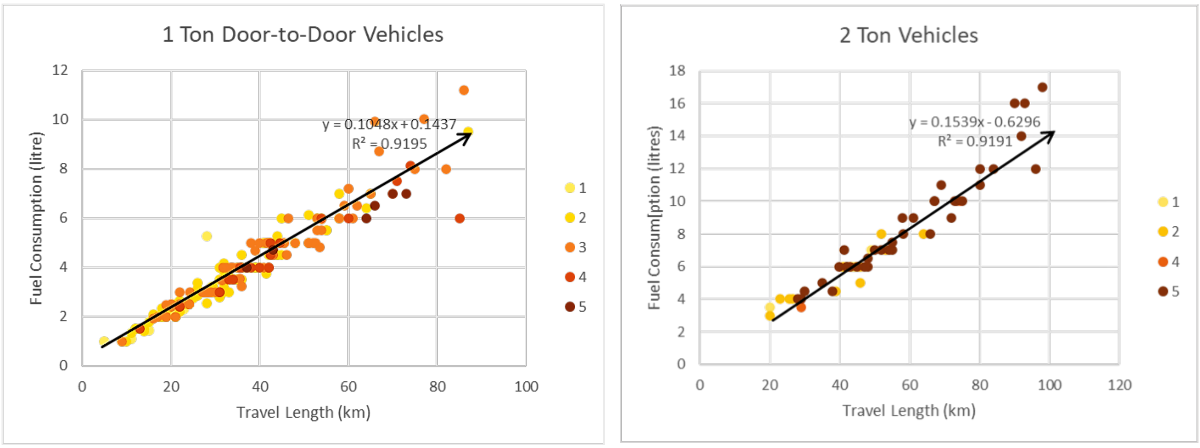


Figure 15: Relationship of Fuel Consumption and Total Travel Length – 1 ton and 2 ton vehicles

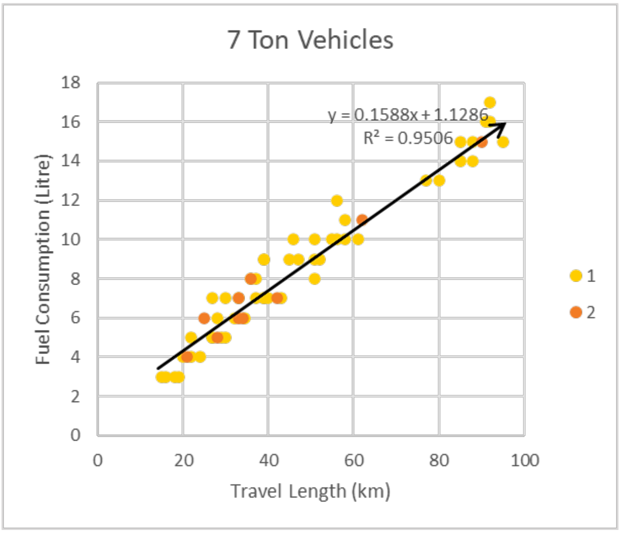


Figure 16: Relationship of Fuel Consumption and Total Travel Length - 7 ton vehicles

For the purpose of the study, the urban factors that determine the length of travel has been explored. Review of relevant literatures (Ivković et.al., 2017; Ou et.al., 2013; Karathodorou et.al., 2009) had indicated that the travel length is dependent on the urban factors like:

- Location of the service area from the RTS,
- Number of trips required to cover a given length of route,
- Building typology and building height along the route assigned for waste collection,
- The size and density of the ward.

5.1.4.1. Location of the Service Area from RTS:

The vehicles which collects waste from an area far from the RTS will by default have longer daily travel length in its log than a vehicle which collects waste from an area near the RTS. Hence, the location of the RTS with respect to the assigned service area for each vehicle impacts the total travel length and indirectly the fuel consumed by the vehicle.

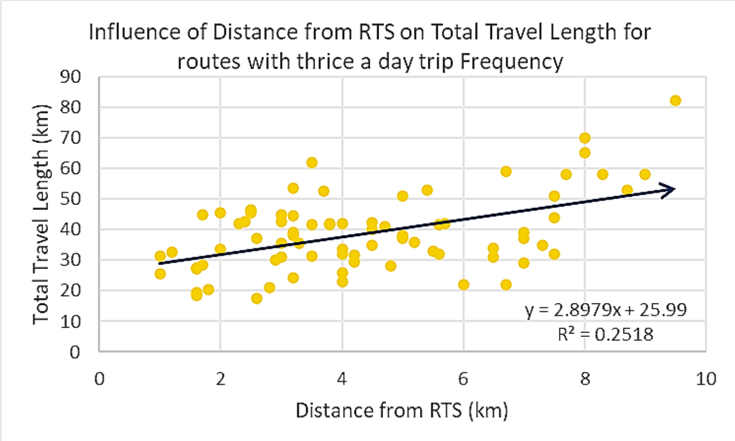


Figure 17: Impact of Distance from RTS on Total Travel Length for a given Trip Frequency

It can be seen from the above graph that with increase in distance between the service area and the RTS, the total travel length of a vehicle increases. Although the relationship is not a perfect one as depicted by a Pearson's correlation coefficient of 0.47, the distance of service area for a vehicle has an indirect influence on the fuel consumption of the vehicle. This relationship is not a direct cause and effect relationship and hence, the correlation coefficient of 0.44 indicates a weak relationship.

5.1.4.2. Number of trips required to cover a given length of route:

For a given route length, the total travel length of two similar waste collection vehicle might be different due to the different trip frequency made by those vehicles. For example, if Vehicle A is assigned lesser POS than Vehicle B, then the former vehicle will complete the collection in a smaller number of trips.

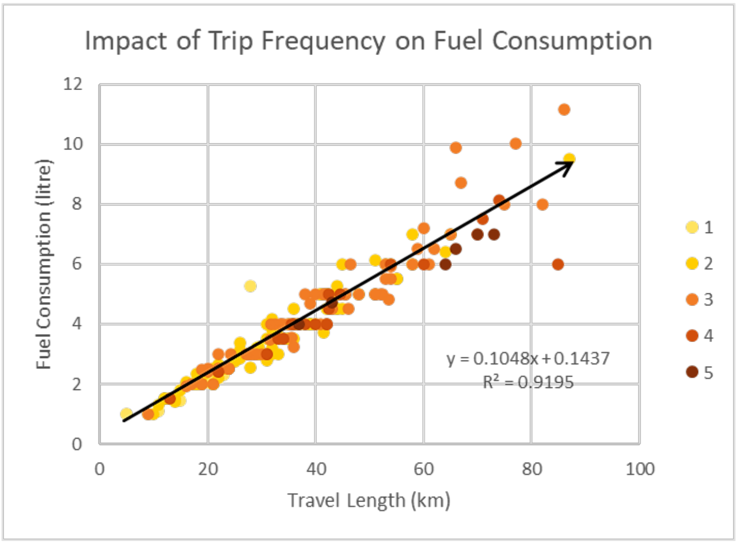


Figure 18: Impact of Trip Frequency on Fuel Consumption

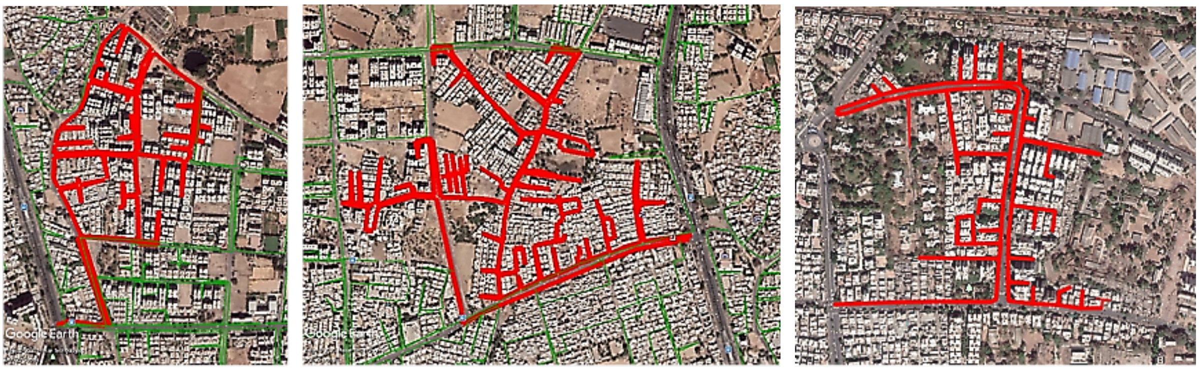
When the trip frequency of vehicles was studied along with their corresponding total travel length, it has been observed that vehicles requiring 5 trips (denoted by dark brown dots) have longer travel lengths compared to vehicles requiring 1 or 2 trips (denoted by light yellow and dark yellow dots).

5.1.4.3. Building Height and Ward Density:

Contribution of the predominant built fabric of the individual routes to the total travel length of a waste collection vehicle has been studied. Building height has been considered as a representative of built fabric in this study. The assumption on which the analyses was done are:

- Building heights determine the amount of waste generated at a point of service.
- With increase in height, a property will generate high volume/mass of waste.
- Clustering of a number of similar buildings will lead to distribution of small routes.
- High amount of waste at a single point of service will lead to vehicle getting filled up quickly and in turn lead to increase in trip frequency.

A densely packed cluster of G+4 and higher storied buildings in urban areas are likely to generate high amount of wastes within a small urban block in contrast to the same amount of waste generation over a large area with scattered low-rise residential development. In such a case, a Door-to-Door waste collection vehicle will be assigned a short route since it is likely to get filled up very quickly. In order to ensure minimum trip frequency during waste collection, the routes passing through dense settlements tend to be shorter than those passing through scattered settlements.



Route A: Chandkheda | Route B: Chandkheda | Route C: Shahibaug

Figure 19: Sample Routes passing through different Urban Settlements

The Cluster Phenomenon can be seen for Route A and Route C where buildings with more than 5-storey are closely packed together. Whereas the vehicle on Route B has to traverse a longer and more complex route due to the spread-out settlement of single and double storey residential units.

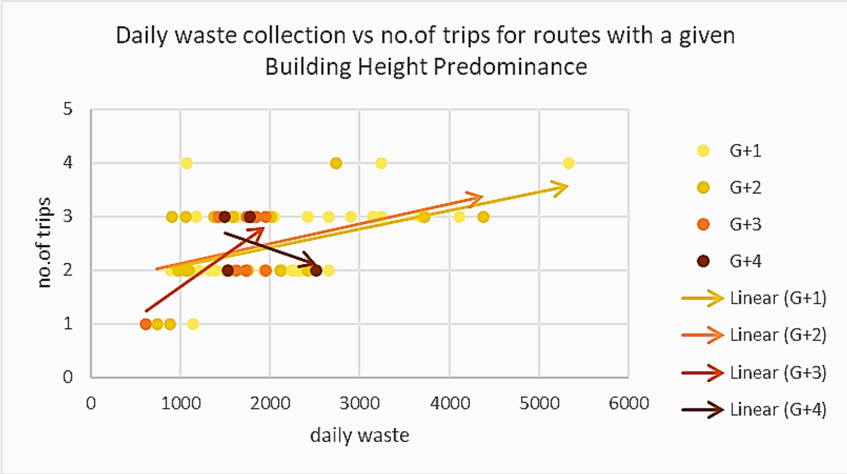


Figure 20: Impact of Predominant Building Height on Waste Amount and Trip Frequency

From the above analyses it can be observed that although waste collection volume does not have an influence on the distribution of routes, it definitely has an influence on the trip frequency of the collection vehicles. Vehicles deployed on routes with predominantly mid- and high-rise (G+4 and above) apartments are assigned a smaller number of point of services as indicated by the low total daily waste collection. This reinstates the cluster phenomenon which leads to smaller route lengths with high degree of clustering. This is contrary to the observations in case of routes with predominantly low-rise (G, G+1 and G+2) buildings where buildings are spatially dispersed and lead to long route lengths.

At the same time the relationship of route length assigned for a cluster on the total travel length has also been studied for clusters with similar built fabric and estimated population density. It might be noted that actual population density has not been used for selection of samples for this analysis.

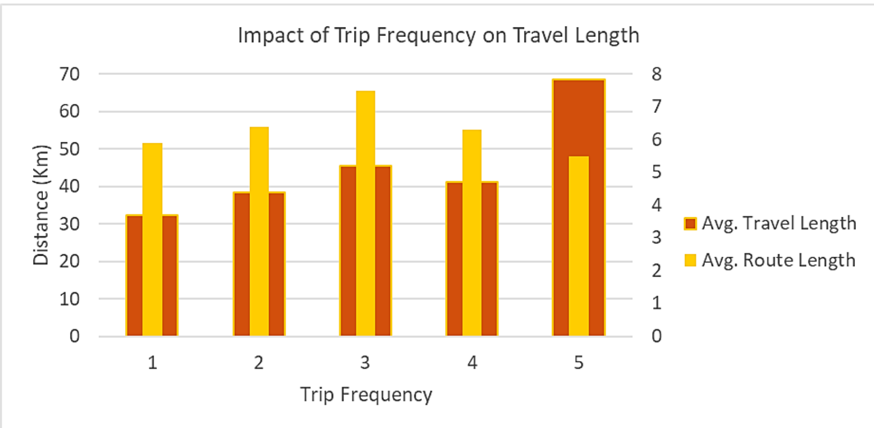


Figure 21: Comparison of Route Length and Travel Length w.r.t. Trip Frequency

It can be observed in the graph above that the vehicles covering a route in a single trip are more likely to have a small total travel length whereas the vehicles which require 3 trips to cover a route have longer total travel length. From the above analyses, it can be said that the route length and trip frequency separately contribute to the total travel length of the vehicles during waste collection process.

The above analyses explain the fuel consumption in any route in the context of the urban characteristics of the individual routes. Although it has been observed that fuel consumption is directly related in positive proportionality with total travel length of a particular vehicle, there are several urban factors that influence the total travel length.

- Firstly, the predominant building height and compactness of the built fabric along a route determines the trip frequency a vehicle has to make to cover an assigned route length.
- Secondly, the spatial position of the transfer station in relation to the area of service contributes to the total travel length for a vehicle and hence indirectly influences fuel consumption.
- Thirdly, higher the trip frequency of a vehicle on a route higher is the total travel length and this increases the total fuel consumption of the vehicle.

Hence, if a service area is in close proximity to the RTS and has predominantly compact built density with high-rise buildings, the fleet servicing that area will consume less fuel than fleet servicing farter areas. However, the choice of fleet also contributes to the total fuel consumption. A high efficiency vehicle serving in localities far from RTS will outperform a low efficiency vehicle serving in localities near the RTS. To understand the variation in fuel consumption across different vehicles in a fleet, the contribution of vehicle parameters in fuel consumption has to be explored separately.

5.2. Impact of Service Delivery Factors in Fuel Consumption

Different types of vehicle on the basis of load carrying capacity has been observed to have different fuel efficiency specified during manufacturing of the vehicle. This fuel efficiency is usually a function of the design and built structure of the vehicle. By the laws of physics, a heavy vehicle will require more energy to move its mass over a given distance and hence consume more fuel in the process than a light weight vehicle. Hence the larger vehicles like Silver Bin Hoppers and Compactors will have low fuel efficiency than the smaller door-to-door collection vehicle. In this study, the impacts of vehicle characteristics in fuel efficiency as well as fuel economy of a vehicle has been analysed.

5.2.1. Fuel Efficiency and Fuel Economy

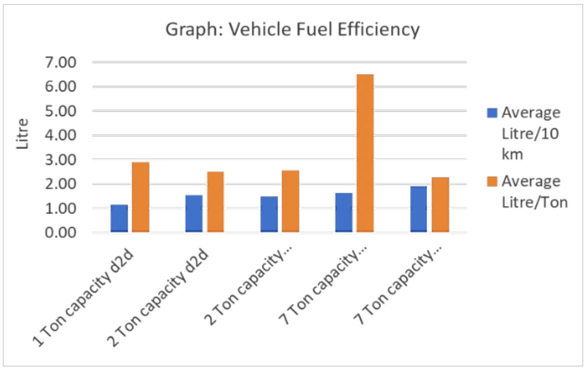
Different countries use the terms Fuel Efficiency and Fuel Economy in different ways. In transport industry the terms are often used interchangeably. For the purpose of this study, the fuel efficiency has been considered in a modified form which is the volume of fuel required by a vehicle to move a unit mass of load over a unit distance. Fuel economy on the other hand can be defined as the fuel consumption per kilometre of travel by the vehicle in loaded condition.

5.2.1.1. Fuel Efficiency across Vehicle Typology (Capacity):

Based on the load carrying capacity, the vehicles in the fleet of both the RTS under this study can be categorised into 3 types:

- 1-ton Vehicles: this category usually comprises of Tata Ace Mega models having a maximum carrying capacity of 1 ton.
- 2-ton Vehicles: this category usually comprises of Tata 407 models having a maximum carrying capacity of 2 ton.
- 7-ton Vehicles: this category usually comprises of Silver Bin Hopper Vehicles and Waste Compactor Vehicles of different models having a maximum carrying capacity of 7 ton.

Analyses has been done using the in-operation values for the vehicles. It has been observed that with increase in capacity the vehicles consume increasing amounts of fuel for travelling a unit distance. When the fuel efficiency of the vehicles was correlated against the tonnage capacity of the vehicle, an increasing trend was observed.



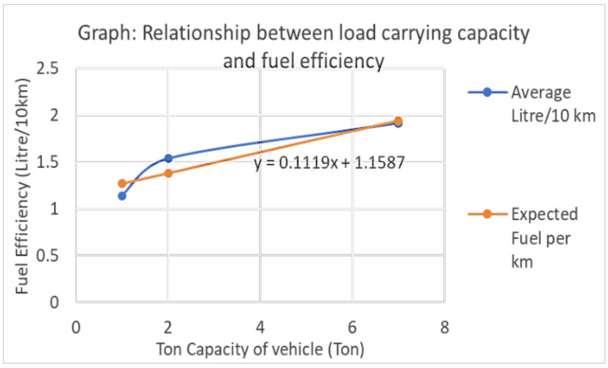


Figure 22: Vehicle Fuel Efficiency across Vehicle Type and Capacity

From the above observation it can be established that the capacity of vehicles is strongly related to the fuel efficiency of the vehicle. Also, although a 1-ton capacity vehicle carries a fraction of the load that a large 7-ton capacity vehicle can carry, the utilisation of these vehicle in the fleet makes them suitable from the perspective of less fuel consumption.

5.2.1.2. Influence of Vehicle Utilisation Efficiency on Fuel Economy:

Utilisation efficiency as considered for this study can be defined as the percentage at which the vehicle operates. It can be calculated taking average payload carried by the vehicle per trip as the percentage of the maximum carrying capacity of the vehicle.

Utilisation Efficiency $=(Average\ Payload\ per\ trip) * \frac{100}{Maximum\ Carrying\ Capacity}$

The vehicles in the current fleet have varying utilisation efficiency. A fraction of Door-to-Door vehicles are utilised above their maximum capacity whereas the non-Door-to-Door vehicles are utilised at very low efficiency.

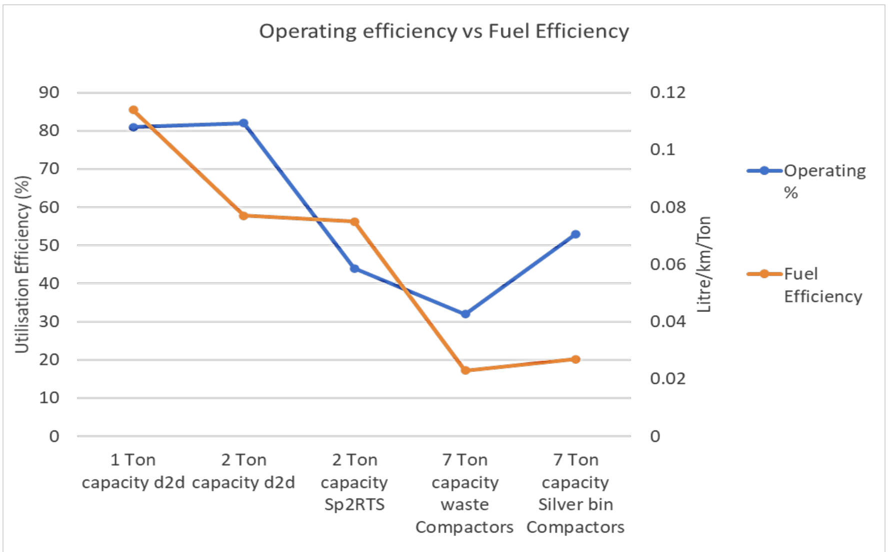
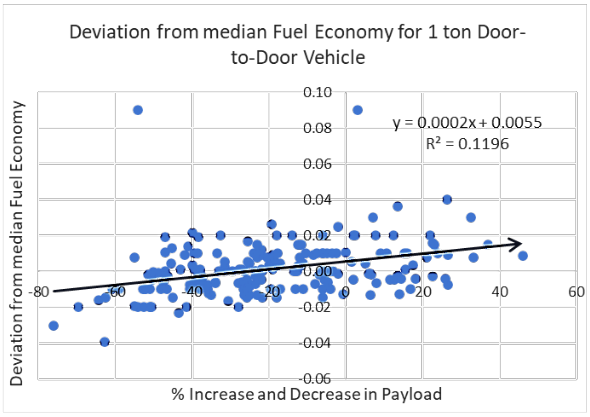


Figure 23: Utilisation Efficiency of Vehicles in the current fleet

From the above observation it can be concluded that the high utilisation of Door-to-Door vehicles in spite of their undesirable Fuel Efficiency can impact on the overall fuel consumption of the system since the distribution of these vehicles have been already established to be maximum in every ward. Hence, the relationship between the utilisation of Door-to-Door vehicles and their Fuel Economy was analysed.



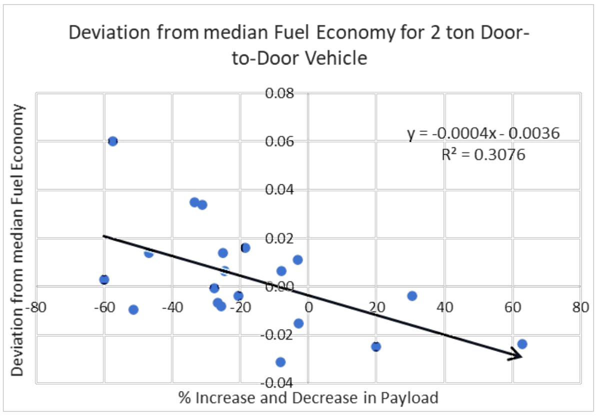


Figure 24: Effect of Payload on Fuel Economy in 1-ton and 2-ton Capacity Vehicles

It can be observed that the fuel requirement increases with increase in payload for 1-ton vehicles whereas it decreases with increasing load for 2-ton vehicles. This shows that the 2-ton vehicles are more fuel efficient for carrying higher loads in case of Door-to-Door collection.

From the above analyses it can be concluded that the large capacity vehicles are more fuel efficient only when utilised to their full potential. The current scenario reflects over-utilisation of 1-ton capacity vehicles which are not fuel efficient compared to the larger capacity vehicles. This over-utilisation leads to higher fuel consumption. It has been established earlier that waste amount generated in a route impacts the trip frequency of Door-to-Door collection vehicles. In such a situation, a 2-ton capacity vehicle is likely to make less trips than a 1-ton capacity vehicle to carry a given waste amount. For example, to collect waste of 4 ton from a assigned route, a 1-ton capacity vehicle will make 4 trips whereas the 2-ton capacity vehicle will make 2 trips. Hence, the larger capacity vehicles at 100% utilisation can lead to significant fuel savings.

Since the 7-ton capacity vehicles are underutilised in the wards under study, the vehicles lead to increase in fuel consumption. This is also due to the fact that the vehicle consumes most of the fuel in running itself as compared to carrying its payload.

5.2.2. Analysis of User Behaviour on Fuel Efficiency

Since the actual fuel consumption of vehicles usually vary from the specifications provided by manufacturers, it can be argued that various in-use behaviours affect fuel consumption during operation of the vehicles. For the purpose of this study, the influence of human skills of waste collection staff and drives on vehicle fuel consumption during the collection process has been analysed.

5.2.2.1. Influence of Average Speed of Vehicle on duty:

It is an established notion in the transportation industry that vehicles consume less fuel per unit distance when running at higher speed than at lower speed. Considering the speed of a vehicle to be a function of the skill of the driver at a given traffic flow condition, the Operational Fuel Economy of the Door-to-Door vehicles were correlated with the average speed of vehicle during collection of waste. It has been assumed that the traffic condition is same for all the routes under consideration for this analysis.

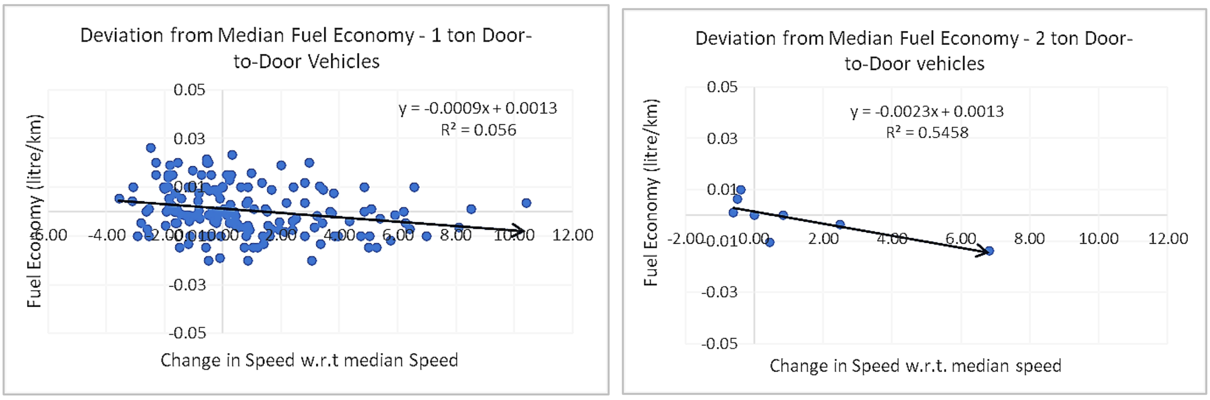


Figure 25: Effect of Average Running Speed on Fuel Economy

The above graphs show that in case of 1-ton vehicles, although a change in speed influences the fuel economy strongly, the change in fuel economy very slight. At the same time, the influence of change in speed on change in fuel economy for 2-ton vehicles is higher as evident from a steeper slope of regression.

5.2.2.2. Influence of Time Taken per km by Driving Staff on Duty:

Driving efficiency during waste collection is a function of the time the waste collection staff spends in loading the vehicle at a given point of service. Since a stretch of route will consist of a number of points of service, the time consumed in covering a stretch of 1 km will reflect the time spent at each point of service. Hence the time taken by a driver to cover 1 km was correlated with the operating fuel economy of the vehicle.

The time taken to cover 1 km is a reciprocal of the average speed of the vehicle on duty. Hence, the trend of fuel economy was found to be increasing with increase in duration. For 1-ton vehicles, the increase in fuel requirement was slight with increase in duration. However, for the 2-ton vehicles, with an increase in duration, the fuel requirement increased significantly.

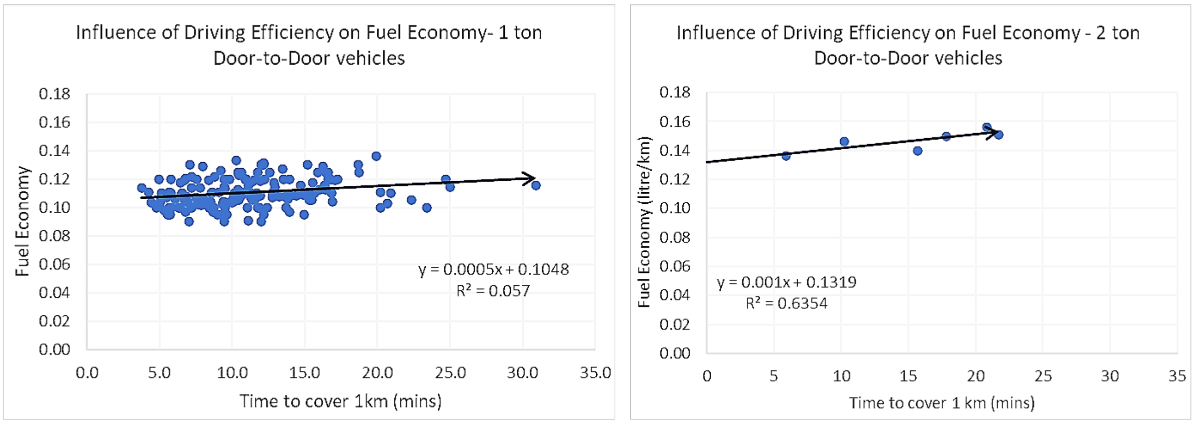


Figure 26: Influence of Duration of waste loading on Fuel Economy

The above graph shows that the 2-ton vehicles are slightly more sensitive to change in collection duration. However, the non-availability of adequate sample for the data in case of 2-ton vehicles, the analyses becomes inconclusive. It must also be noted that very few 2-ton vehicles are deployed in all the wards for Door-to-Door Collection. A richer data set on 2-ton vehicles may result in a different observation.

From the above observation it can be concluded that for 1-ton vehicles, speedy loading of vehicles at the point of service may not influence overall fuel consumption of the fleet, but for the 2-ton vehicles, raising the loading speed will lead to less time spent in covering the route and increase fuel savings significantly. Since the traffic conditions have been assumed to be similar for all routes in this study, it can be said that the 2-ton vehicles respond to change in speed or change in collection time significantly. Hence, assigning skilled drivers and waste collection staff for operating the 2-ton vehicles will lead to higher fuel savings within the fleet. These observations further indicate that a team skilled and efficient driver and waste collection staff can ensure speedy service delivery and at the same time reduce the fuel consumption significantly. An increase in speed by 5 km/h will result in reduction in fuel consumption by 2 litre/100 km.

6. Conclusion and Way Forward

6.1. Conclusion

The study revealed that the collection of Municipal Solid Waste in the city follows a strategic system of route optimisation and distribution in order to ensure 100% service delivery. The 12 wards covered under this study generate an estimated 847 Metric tons of waste out of which 800 Metric tons of waste gets collected through the regular collection system and the rest is collected through on-demand collection system. The fuel consumed to move the 800 Metric ton of waste from all the 12 wards to the respective RTS sums up to 1686 litres per day. Considering the present waste generation in the whole city to be approximately 3800 TPD, it can be estimated that the collection of this waste requires approximately 8000 Litres of Fuel per day. This can be translated to 17 Litres/sq.km. of city area or 130 ml/1000 people of the city population.

Although this implies a rate of 2.1 litre consumption per ton of waste, it can be argued with the support of the results in this study that ward level scenario is more complex in terms of fuel consumption rate. For the 12 wards in this study, the fuel consumption per ton has a wide range of values from 1.05 Litre/Ton for Khadiya to 3.45 Litre/Ton for Chandkheda. The fuel consumption per ton per unit area also varies over a wide range with a minimum of 0.3 Litre/Ton/sq.km. and a maximum of 0.9 Litre/Ton/sq.km. In terms of population, fuel consumption ranges from 0.3 Litres/1000 people to 1.1 Litres/1000 people depending roughly upon the population density and the location of the ward. Hence, in order to explore the city level fuel consumption in collection and transportation of solid waste, ward level data can be used to feed into the City energy Model.

The study of urban land-use, population density and vehicle distribution across the 12 wards has indicated that certain waste collection vehicles are suitable in certain urban conditions. The 2-ton capacity vehicles are more suitable in wards with low density residential developments whereas no vehicle larger than the 1-ton capacity vehicles can be deployed for Door-to-Door waste collection in high density urban settlements. The large compactor vehicles find best fit only in case of wards with predominantly industrial and commercial developments such as Shahpur. In this context, the vehicle distribution in Ahmedabad follows an efficient pattern considering the wide range of population density and land-use in the wards.

The comparison of fuel consumption across the wards has revealed the impacts of urban form, ward characteristics and route characteristics on the fuel consumption. Ward shape and size has a significant influence on the route length assigned for waste collection. Dense habitations are more likely to result in shorter routes within the wards. The route length in combination of the waste generation in the service areas can result in increase or decrease in the total travel length for waste displacement since more waste requires more trips to and from the RTS. Also, if the service areas are located far from the

RTS, the travel length increases significantly. All these factors combined together results in rise in fuel consumption in the waste collection system.

Apart from the urban factors, the choice of vehicles and the staff handling the vehicles and collection process also influence the degree of fuel efficiency in the waste collection system. Waste collection vehicles in Ahmedabad are deployed such that 100% waste collection can be ensured. Hence the number of 1-ton capacity vehicles are maximum in the fleet as these vehicles can enter narrow lanes for Door-to-Door collection. Too many 1-ton vehicles in the fleet and over-utilisation of such vehicles significantly raises the overall fuel consumption in a two-fold way. Firstly, fuel consumption of these vehicles increases with increase in payload above their carrying capacity. Secondly, these vehicles will require more trips to cover their assigned routes. On the other hand, the 2-ton Door-to-Door vehicles exhibit better fuel efficiency than the 1-ton vehicles as they can carry more waste in few trips. However, the larger vehicles of 7-ton capacity do not prove to be performing efficiently in Ahmedabad due to the underutilisation of the full potential of the vehicle. Each of the 7-ton Compactor vehicles are usually assigned a whole ward and the route of the vehicles vary on daily basis on account of demand for waste removal. The Silver Bin Hoppers are assigned fixed number of bins for collection and often these bins remain unfilled. Such scenarios compel the drivers to run the vehicles on long routes without the vehicles getting filled to their capacity.

The driving speed and efficient time management during loading of waste at point of services also influence the fuel consumption in the collection process. A team skilled and efficient driver and waste collection staff can ensure speedy service delivery and at the same time reduce the fuel consumption significantly. An increase in speed by 5 km/h will result in reduction in fuel consumption by 2 litre/100 km.

In a city like Ahmedabad, the ULBs take the final decision of regarding the procurement of vehicles/ services related to the MSW collection system. Further expansion of the city requires expansion as well as improvement in the level of service which involves a cost which the ULB has to bear by itself. With rapid urbanisation, most Indian cities still struggle with efficient collection and transportation of solid waste and often resort to easily deployable fleet of vehicles for the purpose. Improper investigation into the suitability of vehicles that are selected through procurement and service contract may lead to higher costs to the ULB in terms of fuel expenses. The study has shown the parameters of such investigation which can help the ULB to decide on the number of vehicles of certain types that can be deployed. The fuel requirement of a city in providing MSW collection and transportation services can be estimated when the following data are known:

- Capacity of the vehicles deployed
- Fuel efficiency of the vehicles
- No. of Refuse Transfer Station

- Distance of RTS from the area of collection service
- Length of route assigned
- No. of trip required by a vehicle for a given fixed waste amount.

6.2. Way Forward

The overall energy footprint of a city requires a study of the city energy model for all the services provided in the city. In such a study, it is essential to consider the local variations in fuel consumption for a service. This study has been limited to a small sample of 12 wards out of the 48 wards in Ahmedabad. For Detailed exploration of relationship and variations in of Fuel Consumption in different wards, the study needs to be scaled up to include richer sample. The up-scaling of the analyses presented here should include built floor space data for each ward in order to establish the range of fuel consumption rate per sq. m. of floor space in certain urban settlements. Similarly, the vehicle characteristics need to be considered in order to accurately study the suitability of vehicle distribution strategies across different urban settlements. The potential of fuel transition from Diesel to CNG or Bio-Fuels and its contribution to energy savings can also be studied in the context of circular energy and Waste-to-Energy strategies. Additionally, the amount of waste reduction possible through decentralised waste treatment at RTS can be studied since reduced waste will require less vehicle and less fuel for transport to Landfill. The study might be further up-scaled to other Indian cities working on similar MSW Management Models and results can be compared.

On the other hand, the Municipal Corporations should set targets for optimum fuel consumption and investigate into the suitability of different collection vehicles before procurement of the vehicles. The allocation of routes through route optimisation can be done cluster wise such that vehicles do not require to make multiple trips due to excess waste generation from any locality. While this study has assumed the sample routes selected are already optimized, the extent of current route optimization can be further evaluated through GIS mapping. Also, skills and efficiency of the waste collection staff, both the driver and the helper also should be evaluated by the ULB to ensure fuel savings. Initiatives to educate the staff in fuel conservation techniques of driving the vehicle can also increase fuel savings. Special attention is required in the drafting of service contracts for waste collection systems. Such contracts can include the reporting of daily fuel consumption data by the contracted agencies into a centralised fuel energy database. Additionally, such instructions in the contracts may be accompanied with penalties for defaulters. The ULB can also decide to implement the RTS system of waste transfer and explore the potential of decentralised waste treatment at the RTS. An informed decision making by the ULBs while incorporating "Fuel Consumption" as an evaluation parameter for procurement of services can lead to significant fuel savings in the waste collection system. Such a fuel saving if augmented with energy generation within the Solid Waste value chain can result in lower cost to the ULB in service provision. User charges can be reduced to more acceptable limits for the citizens. Hence, the inclusion of Fuel Efficiency within the Solid Waste Management has a potential to improve the trust on municipal services on part of residents as well as improve service delivery on part of the ULB.

References

Buclet, N., & Godard, O. (2001). The Evolution of Municipal Waste Management in Europe: how Different are National Regimes. *Journal of Environmental Policy and Planning*, 303-317.

Coffey, M., & Coad, A. (2010). *Collection of Municipal Solid Waste in Developing Countries.* United Nations Human Settlements Programme. Nairobi: United Nations Human Settlements Programme (UN-HABITAT).

Herbert, L. (2007). CENTENARY HISTORY OF WASTE AND WASTE MANAGERS IN LONDON AND SOUTH EAST ENGLAND. London, England: Chartered Institution of Wastes Management (CIWM).

Hickman, H. L. (2003). *American Alchemy: The History of Solid Waste Management in the United States.* Santa Barbara, California, USA: Forester Press.

Ivkovic, I. S., Kaplanovic, S. M., & Milovanovik, B. M. (2017, January). Influence of Road and Traffic Conditions on Fuel Consumption and Fuel Cost for Different Bus Technologies. *THERMAL SCIENCE, 21*, 693-706. doi: 10.2298/TSCI160301135I

Joshi, R., & Ahmed, S. (2016, February 17). Status and challenges of municipal solid waste management in India: A review. (2016). New Delhi, NCT Delhi, India: Cogent Environmental Science. doi:10.1080/23311843.2016.1139434

Karathodorou, N., Graham, D. J., & Noland, R. B. (2009). *Estimating the Effect of Urban Density on Fuel Demand.* Imperial College London. London: Elsevier Science Direct. doi:10.1016/j.eneco.2009.05.005

Marshall, J. D. (2008, May 1). ENERGY-EFFICIENT Urban Form: Reducing urban sprawl could play an important role in addressing climate change. Minnesota, USA. Retrieved from https://pubs.acs.org/doi/pdf/10.1021/es087047l

McKinnon, A. (2010). increasing fuel efficiency in the road freight sector. In *GREEN LOGISTICS: Improving the environmental sustainability of logistics* (pp. 242-253). Kogan Page Limited .

Menon, A., & Bandivadekar, A. (2016, December). LIGHT-COMMERCIAL VEHICLES IN INDIA, 2014-15: TECHNOLOGY ASSESSMENT AND INTERNATIONAL COMPARISONS. Washington DC, USA: International Council on Clean Transportation. Retrieved from https://theicct.org/sites/default/files/publications/India%20LCVs_White-Paper_ICCT_23122016.pdf

Mohan, D., Goel, R., Guttikunda, S., & Tiwari, G. (2014). *PROMOTING LOW CARBON TRANSPORT IN INDIA: Assessment of Motor Vehicle Use Characteristics in Three Indian Cities.* New Delhi, India: Magnum Custom Publishing.

Ou, J., Liu, X., Li, X., & Chen, Y. (2013, September 28). Quantifying the relationship between urban forms and carbon emissions using panel data analysis. Guangzhou, People's Republic of China. doi:10.1007/s10980-013-9943-4

Vaish, S., Iyer, M., Sachin, S., Rawal, R., & Chouhan, S. (2019). *Electricity consumption in municipal services: Relationship with the urban form.* CEPT University, Faculty of Planning. Ahmedabad: Centre for Advanced Research in Building Science and Energy (CARBSE), CEPT University.

Wang, L., Kelly, K., Walkowicz, K., & Duran, A. (2015). Quantitative Effects of Vehicle Parameters on Fuel Consumption for Heavy-Duty Vehicle. *SAE International*. doi:10.4271/2015-01-2773

Zacharof, N. G., Fontaras, G., Ciuffo, B., Tsiakmakis, S., Anagnostopoulos, K., Marotta, A., & Pavlovic, J. (2016). *Review of in use factors affecting the fuel consumption and CO2 emissions of passenger cars* . Luxembourg: European Union. doi:10.2790/140640

Appendix A Sample Questionnaire for SSI

Questionnaire for SSI at RTS					
1	What is the Total Handling Capacity of the RTS?				
			TPD		
2	How many Wards does the RTS serve?				
3	How many vehicles in each category?				
	Tonnage	No. of Vehicles		Fuel Type	No.of Vehicles
4	How many outgoing vehicles ?				
	Tonnage	No.of vehicles			
5	Dry Waste recovery arrangement present or not?				
	Yes	No			
6	What provision for dry waste material recovery practiced?				
7	Which are the agencies managing the fleet?				
	Agency Supervisor	Type of vehicle	No. of Vehicle		
8	Ward wise vehicle distribution?				
9	Weighbridge Records acessibility?				
	Yes	No			
10	Agency wise vehicle refueling log accessibility?				
	Yes	No			
11	Tracking System used for incoming and outgoing vehicles?				
	Incoming:				
	Outgoing:				
12	Parking Facility for vehicles present or not?				
	Yes	No			
	If Yes, number?				

Questionnaire for SSI at Ward Office					
1	How many vehicles in each category?				
	Tonnage	No. of Vehicles		Fuel Type	No.of Vehicles
2	Start and End Time of the daily waste collection?				
3	Which are the agencies managing the fleet?				
	Agency Supervisor	Type of vehicle	No. of Vehicle		
4	Availability of Route Maps?				
	Yes	No			
5	Route Tracking Accessible?				
	Yes	No			
6	How are route distributed/allocated to vehicles?				

Appendix B Sample Weighbridge Records

AHMEDABAD MUNICIPAL CORPORATION
WEST ZONE TRANSFER STATION
SOLID WASTE MANAGEMENT
Log Book / Statement

Searching Details | Incoming | AGENCYWISE DETAILED

Agency : All Agencies
Date : 29/01/20 To 29/01/20
Agency Name
29/01/20

Contract Type : DOOR TO DOOR
Printed On 01/02/20 9:02AM

SlipNo	Vehicle No	Cont. Spot	Ward	G. Wt.	Gross Tm	T. Wt.	Tare Tm.	Net Wt.
				2700	9:06:27AM	1610	9:10:03AM	1090
				2100	9:08:58AM	1570	9:14:28AM	530
				2030	9:19:03AM	1510	9:24:59AM	520
				2170	9:35:10AM	1440	9:37:54AM	730
				2640	9:39:50AM	1640	9:47:12AM	1000
				1950	9:44:03AM	1500	9:50:17AM	450
				2410	9:45:22AM	1480	9:49:52AM	930
				2280	9:55:49AM	1490	10:00:34AM	790
				2250	10:06:56AM	1600	10:11:42AM	650
				2520	10:35:26AM	1490	10:40:27AM	1030
				2920	10:48:56AM	1490	10:55:07AM	1430
				2360	10:49:58AM	1510	10:56:34AM	850
				2270	10:50:32AM	1530	10:58:19AM	740
				4440	10:59:07AM	2920	11:02:03AM	1520
				2330	11:06:16AM	1520	11:12:26AM	810
				2170	11:14:58AM	1570	11:21:20AM	600
				2470	11:15:30AM	1610	11:27:55AM	860
				1980	11:30:48AM	1490	11:40:40AM	490
				2020	11:45:02AM	1480	11:48:58AM	540
				2670	12:03:31PM	1680	12:10:52PM	990
				2890	12:10:53PM	1530	12:13:54PM	1360
				2010	12:16:49PM	1460	12:20:52PM	550
				2230	12:28:53PM	1440	12:31:05PM	790
				2430	12:33:57PM	1490	12:35:10PM	940
				2440	12:46:30PM	1500	12:47:57PM	940
				2350	1:02:14PM	1610	1:07:19PM	740
				2040	1:10:15PM	1520	1:12:20PM	520
				2200	1:12:36PM	1560	1:14:14PM	640
				2640	1:17:34PM	1670	1:20:31PM	970
				2830	1:23:09PM	1440	1:26:04PM	1390
				2760	1:46:43PM	1450	1:55:44PM	1310
				3180	1:52:32PM	1490	1:57:22PM	1690
				2750	1:53:11PM	1460	2:01:01PM	1290
				2600	1:54:03PM	1490	2:01:22PM	1110
				2940	2:22:44PM	1630	2:26:48PM	1310
				3140	2:48:37PM	1460	2:51:43PM	1680
				2100	2:50:06PM	1480	2:52:53PM	620
				2640	2:52:49PM	1480	4:43:37PM	1160
				1850	2:53:16PM	1500	2:59:12PM	350
				4660	3:20:24PM	2920	3:26:35PM	1740
				3150	3:31:50PM	1480	3:33:44PM	1670
				3700	3:57:51PM	1520	4:01:29PM	2180
				2860	4:14:33PM	1490	4:17:35PM	1370
				1860	4:39:13PM	1480	4:43:44PM	380
				3050	6:30:29PM	1610	6:34:02PM	1440

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Appendix C Sample Vehicle Refuelling Log

Sl. No.	Km (last two days)	Fuel (l)	Fuel Type	Ward
1	87	13	Diesel	Chandkheda
2	92	12	Diesel	Chandkheda
3	128	16	Diesel	Chandkheda
4	93	13	Diesel	Chandkheda
5	82	11	Diesel	Chandkheda
6	99	13	Diesel	Chandkheda
7	104	13	Diesel	Chandkheda
8	131	12	Diesel	Chandkheda
9	140	12	Diesel	Chandkheda
10	130	13	Diesel	Chandkheda
11	149	13	Diesel	Chandkheda
12	154	13	Diesel	Chandkheda
13	164	14	Diesel	Chandkheda
14	133	13	Diesel	Chandkheda
15	117	10	Diesel	Chandkheda
16	116	10	Diesel	Chandkheda
17	116	10	Diesel	Chandkheda
18	107	10	Diesel	Chandkheda
19	106	14	Diesel	Sabarmati
20	87	12	Diesel	Sabarmati
21	90	12	Diesel	Sabarmati
22	70	8	Diesel	Sabarmati
23	67	7	Diesel	Sabarmati
24	170	14	Diesel	Sabarmati
25	85	9	Diesel	Sabarmati
26	120	11	Diesel	Sabarmati
27	96	10	Diesel	Sabarmati
28	122	10	Diesel	Sabarmati
29	176	12	Diesel	Sabarmati
30	112	10	Diesel	Sabarmati
31	128	10	Diesel	Sabarmati

Appendix D Route Details

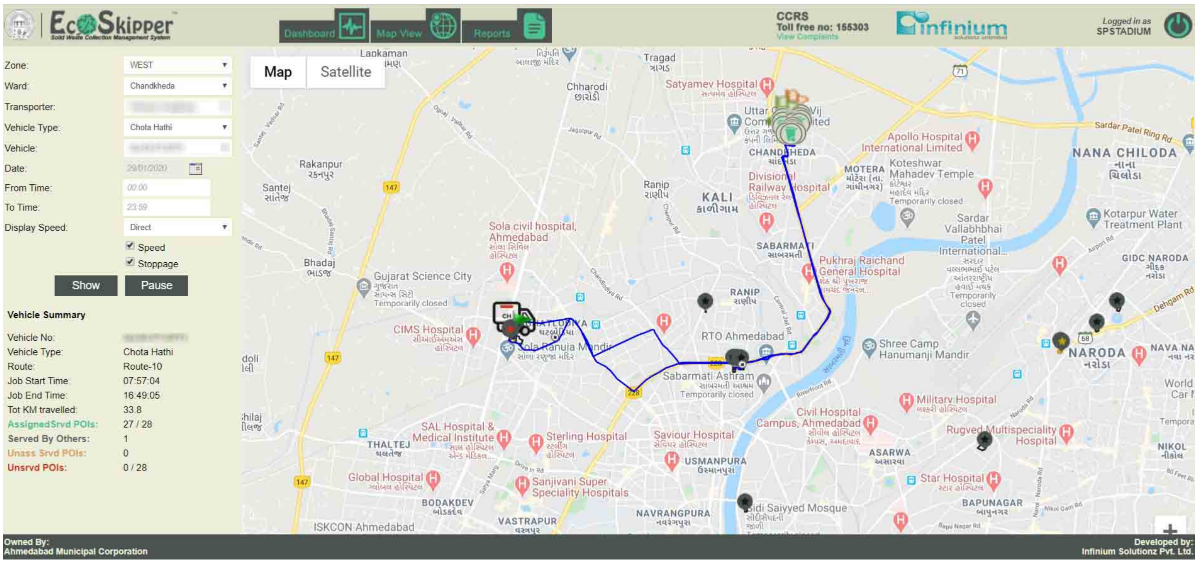

Figure 27: Route of sample vehicle in Chandkheda Ward

Figure 28: Google Earth KML of the sample Route

Kasturbhai Lalbhai Campus,
University Road,
Ahmedabad - 380009, Gujarat, India
www.cept.ac.in/carbse

www.inumber.org