PLANNING, DESIGN, AND OPERATIONAL ANALYSIS OF UNDERGROUND FREIGHT TRANSPORTATION SYSTEMS WITH INDIVIDUAL AUTONOMOUS VEHICLES

by

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All the credit and honor of this dissertation

goes to my parents for their

endless love, support and encouragement.

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Abstract

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Given the increases in freight transportation demand, the current infrastructure for freight transportation appears insufficient. Moreover, the future development of capacity for freight transportation infrastructure seems to be limited. Based on a U.S. DOT report, most of the U.S. freight transportation infrastructure's construction dates back to the 1960s. This puts a heavy burden on the national highway and railroad systems. The growing demand for freight will increase truck traffic on both urban and rural highways. The increase in truck traffic on highways will result in multiple challenges, including traffic congestion, security concerns, infrastructure deterioration, environmental pollution, energy consumption, increase in crash and fatality rates and loss of productivity. An Underground Freight Transportation (UFT) system can play a significant role in meeting some of the future capacity shortcomings in the above-ground freight transportation. UFT offers multiple benefits: decreasing truck traffic on highways, reducing rail traffic, reducing energy consumption, reducing noise and air pollution, promoting safety and security, and enhancing the reliability of freight delivery. A UFT system is an autonomous transportation system that carries freight in individual capsules or flat-bed gondolas within tunnels or pipelines. This research starts with the planning of a UFT system for multiple locations in

Texas and then identifies UFT design components. Moreover, this research formulates UFT operational parameters and develops relations among those parameters. Additionally, different propulsion systems have been studied for UFT systems and the required power and energy consumption of the propulsion system is calculated.

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Chapter 1. Introduction

1.1. Background

Along with population growth and economic development, the need for commodities will increase. Based on a report from the American Trucking Association (ATA), freight transportation will increase by 30% in the next 10 years (American Trucking Associations, 2016). The rise in freight transportation stems from population growth, increase in the need for energy, and the expansion of global trade. A report by Department of Transportation (DOT) entitled “U.S. Freight Transportation Forecast to 2026” declares that although trucking remains the major mode of freight transportation, its market share will drop from 69% to 65% in competition with new emerging modes of transportation. The same applies to railroad freight transportation, where its share is expected to decrease from 14% to 12% despite the investments in this industry (McNally, 2015).

The DOT report cites pipelines and intermodal systems as the fastest growing modes of freight transportation. This is due to the demand for a more timely, reliable, and safer freight transportation system. The U.S. Department of Transportation believes that the rise in the role of intermodal systems lies in the importance of infrastructure connecting two different modes of transportation, especially at international gateways (Mallett, 2004).

The freight pipeline transportation system is neither a conventional rail system nor a replacement for the truck transportation system. Freight pipeline transportation is a new intermodal system for freight transportation, which is designed to complement the latter systems in meeting the anticipated future growth in freight transportation. The Texas transportation system is critical to the US due to the North American Free Trade Agreement (NAFTA) between the US, Mexico, and Canada. Freight transportation in the Port of Houston places it the first ranked US port in foreign tonnage. Through 2030, NAFTA trade will increase by nearly 207 percent by tonnage (Najafi, 2017). This will have a profound impact on the Texas highway and rail systems. Therefore, increasing the capacity of the freight transportation system is a must.

1.2. Problem Statement

Despite the increases in freight transportation demand, the current infrastructure for freight transportation is insufficient. Moreover, the development capacity of freight transportation infrastructure seems to be limited for future growth. Based on the U.S. DOT report, most of the U.S. freight transportation infrastructure's construction dates to 1960 (Schmitt, 2008). This puts a high burden on the national highway and railroad systems. The growing demand for freight will increase truck traffic on both urban and rural highways. The increase in truck traffic on highways will result in multiple challenges, including: traffic congestion, security concerns, infrastructure deterioration, environmental pollution, energy consumption, increase in crash and fatality rates and loss of productivity (Douglas, 2003).

Regarding the railroad system capacity for freight transportation, predictions show that there will be a dramatic rise in congestion on the railroad system by 2035. The Association of American Railroads suggests an analysis method based on volume-to-capacity comparisons similar to what is done in highway level of service calculations. The results show that rail lines with unstable flows and service break-downs will increase from 108 miles in 2008 to almost 16,000 miles (30 percent of the national rail network) in 2035, considering no increase in current rail line capacity (Schmitt, 2008). Texas, as the largest state in the 48 contiguous states, has a long border with Mexico and access to the Gulf of Mexico, which brings tremendous trading opportunities. In fact, Texas with its three major sea ports (Port of Houston, Port of Corpus Christi, and Port of Beaumont) is one of the main entrances for international freight to the U.S. (Bureau of Transportation Statistics, 2017).

Based on the “Texas NAFTA Study Update” prepared for Texas Department of Transportation (TxDOT), tonnage of freight due to the North American Free Trade Agreement (NAFTA) on Texas highways and railroads is forecasted to increase by nearly 207 percent from 2007 to year 2030. Truck tonnage will grow by 251 percent while rail tonnage is forecasted to increase only 118 percent. The number of trucks carrying NAFTA goods will increase by 263 percent, and the number of rail units will grow by 195 percent (Cambridge Systematics, 2007). This increase in freight volume will have a tremendous impact on the Texas transportation infrastructure.

1.3. Research Contribution

The three main elements in the design and implementation of an Underground Freight Transportation (UFT) system include geometric and system design, analysis of operational attributes, and construction method. A comprehensive economic analysis of UFT system requires results from both the construction methods and operational attributes. Most studies on UFT systems are focused on the economic feasibility and construction methods of UFT systems. A few projects have developed schematic designs for their UFT systems, which have been specific to the project condition and needs and cannot be used as general typical designs.

This research seeks to provide a typical geometric design that can be used as a reference in the design of other UFT systems. Moreover, this research aims to formulate UFT operational parameters and develop relations among those parameters such as headway, capacity, and speed. Based on the literature review, a general lack of resources in the design of UFT systems exists and no studies focus on an operational analysis of a

UFT system. Figure 1.1 shows the relation among UFT system elements and total cost estimation.

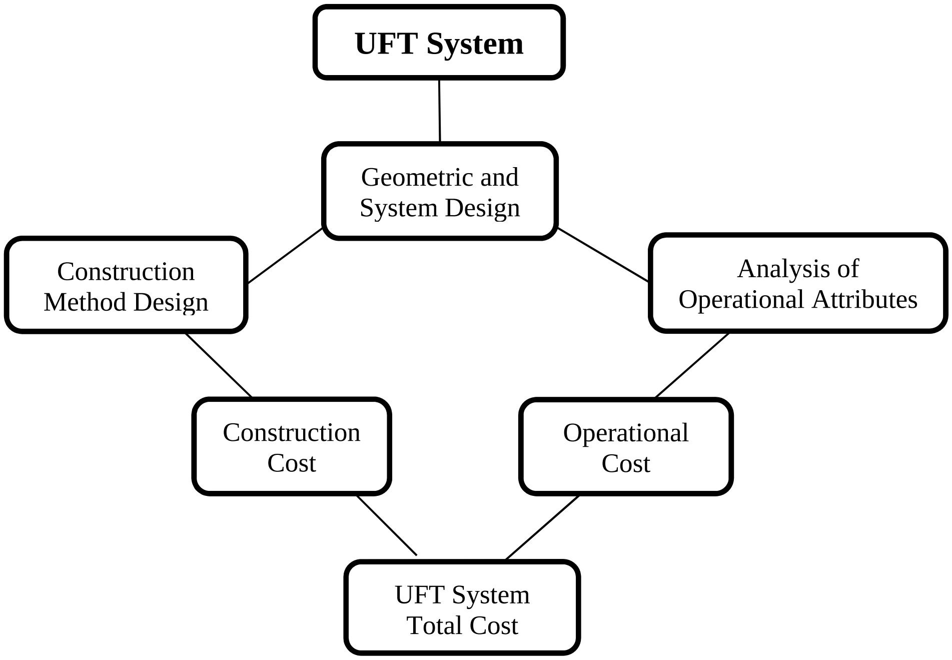


Figure 1.1 UFT System Elements Analysis

1.4. Literature Review

Underground transportation systems have long been used for passenger transportation. The London Metro was opened first in 1863, and the New York subway has been in use for more than 110 years. Two main reasons can be recognized in emerging subway systems: In the late 19th century, cities were growing rapidly, and cities became more crowded and polluted. On the other hand, new technologies allowed tunneling below the ground as well as creation of mass transportation vehicles (Haupt, 1891). Similar conditions apply to today's freight transportation. There is a large demand for freight in urban areas, which makes highways more congested and unsafe. Moreover, the tunneling technology with the invention of Tunnel Boring Machines (TBM) has advanced substantially. These factors make the time ripe to consider using underground pipelines for freight movement.

In fact, the idea of using underground space for transferring commodities dates back to the 1970s when research on a freight pipeline was funded by the U.S. Department of Transportation. This research entitled “Transport of Solid Commodities via Freight Pipeline” and concentrated mostly on application of freight pipeline in mining, refineries, and factories (Zandi, 1976). Almost at the same time, the idea of using pipelines for transferring freight developed in Europe and Japan. In 1977, the British Hydromechanics Research Association (BHRA) launched its first full-scale pneumatic capsule pipeline test. In 1982, Japan started its first commercial pneumatic capsule pipeline called “Sumitomo” (Liu 2000).

Currently, the need for an underground freight transportation system is increasingly more evident, and some novel and bold ideas have been created in the last decade. “CargoCap” is one of these novel ideas, which was developed in Germany. This system is designed to connect international destinations and accommodates pallet-size loads in capsules moving in long pipelines (Stein, 2003). Meanwhile, in the UK, another novel idea evolved. The suggested scheme provides pipeline facilities for transferring food and is called “Foodtubes.” This system is designed to connect main food producers to large retailers, so consumers can have access to fresh food (Hodson, 2008).

In the Netherlands, the importance of flower exports made the authorities, along with major flower producers and the Schiphol airport, design an underground pipeline system that can deliver fresh flowers to the airport as fast as possible. This system is designed to be fully automated and uses 200 to 400 Automatic Guided Vehicles (AGVs) for transporting freight in routes of 16 to 25 miles (van der Heijden et al., 2002). There are newer UFT systems in Europe which were designed or tested after 2010: “Mole” solution in the UK, uses Linear Induction Motors (LIM) and is in the laboratory test phase. The Pipe&Net system in Italy also uses a LIM as the propulsion system and is designed to connect two major hubs. The Underground Container Mover (UCM) is a UFT system that is designed in Belgium in order to solve the freight transfer problem in Belgium ports (ISUFT, 2015).

A comprehensive study of freight pipelines was done by the American Society of Civil Engineers (ASCE) (ASCE Task Committee on Freight Pipelines, 1998). This study concludes that freight pipelines will face increasing use in the future because of their relatively lower cost, higher reliability, safety, security, technological advancement, reduced noise and air pollution, and energy efficiency. In 1991, the National Science Foundation (NSF) established a capsule pipeline research center at the University of Missouri, Columbia. The initial focus of the center's research was to develop a coal log pipeline (CLP) technology for commercial use (Liu, 1993). In later years, an underground freight transportation system was proposed for New York City by Liu and colleagues at the University of Missouri. This project analyzed the feasibility of using modern technologies for constructing an underground freight transport system in New York City (Liu, 2004). This research was one of the early studies that suggested Linear Induction Motors (LIM) as the propulsion system for UFT.

Some of those projects include the Sydney Freight Circle for container transport from the Port of Sydney to seven distribution warehouses (Fiars, 2009), the container port expansion project in Shanghai (Guo, 2008), and currently operating systems in the mining industry (Liu 2005), (Kosugi, 1999). A comprehensive study for constructing a pneumatic capsule pipeline in New York city is prepared by Liu (Liu, 2004). This study proposes a network of tunnels below ground in New York City with scattered stations that use elevators for bringing up pallet-size loads to the surface. In addition, the Freight Shuttle System proposed by Roop (Roop 2001) was examined in Texas to connect the San Antonio-Austin metropole to DFW. Switzerland is planning to construct a comprehensive freight pipeline system to connect major cargo hubs and distribution centers to major cities. This system, named “Cargo Sous Terrain,” is fully automated and is designed for pallet- and crate-size loads. The first phase of this system is expected to launch by 2030 (Cargo Sous Terrain AG, 2016).

The most well-known system of pipeline transportation is the Hyperloop One. This system was originally designed to transport people in vacuum tubes in order to maximize speed. With the increase in the importance of cargo transportation, the Hyperloop One system is taking steps to design a hybrid system that can carry both people and cargo. Pilot tests for this system are launched successfully, and more studies are moving toward a full-scale system in Texas, Colorado, Florida, Chicago, Dubai, and UK (Hyperloop One, 2016).

A few studies were completed in Texas for constructing a UFT pipeline. A comprehensive study for evaluating the construction of a UFT system was done by the Texas A&M Transportation Institute (TTI). This research identified five major components of a UFT system design: underground tunneling, power, transportation system, material handling, and control systems. In this project, a UFT system was designed to carry pallets rather than truck-size loads (Roop, 2002). Moreover, another research study on a UFT system was done in 2016 by the Center for Underground Infrastructure Research and Education (CUIRE). This research was funded by the Texas Department of Transportation. The goal of this research was to integrate UFT systems into existing highways. The idea was that by constructing a UFT system in the right-of-way of existing highways, the cost of land purchase for a new freight transportation system (rail or highway) can be saved. In this research, different aspects of UFT construction, including planning, design, operation, construction method, cost estimation, environmental impact, finance and public-private partnership are assessed (Najafi, 2016).

A literature review on previous freight pipelines studies (either proposed as a concept or constructed as a pilot project or systems already in operation) were examined. These studies included studies conducted for the Federal Highway Administration by Volpe, the National Transportation Systems Center, and others (Vance, 1994). A focus of the literature review was innovative approaches that may have been undertaken in these projects, such as innovative construction methods, propulsion systems, loading/unloading mechanisms. These studies have formed the basis for schematic designs of various elements of the proposed UFT line.

1.5. UFT Research and Projects

This dissertation is the result of almost 4 years of research on underground freight transportation systems and cargo pipelines. It started with the application for graduate research awards for applied- research in airport-related issues in May 2014. This was a national competition for airport and aviation related research sponsored by the U.S. DOT Federal Aviation Administration (FAA) and administered by the Transportation Research Board's (TRB) Airport Cooperative Research Program (ACRP). The competition included submitting the project proposal and research plan under a FAA faculty mentor. The submitted proposal under Dr. Ardekani's supervision was entitled "Analyzing and Modeling underground Cargo Transfer Systems to Off-site airport Warehouses." Although this application was not successful, it became a starting point in our UFT research.

The second project for UFT was entitled “Integrating Underground Freight Transportation into Existing Intermodal Systems.” This project was funded by the Texas Department of Transportation (TxDOT) and conducted by Dr. Najafi, Dr. Ardekani and Dr. Shahandashti. The goal of this research was to study the feasibility of constructing UFT systems in the right-of-way of existing highways. This project included planning, design and operation of a UFT system and its terminal. This project started on May 2015 and lasted for almost two years. Afterward, in May 2017, the North Central Texas Council of Government (NCTCOG) funded a project to design an intermodal freight pipeline for DFW Airport. This project aimed to decrease the truck traffic at the DFW Airport and enhance safety, security and environmental quality.

1.6. Dissertation Configuration

This dissertation consists of six chapters. The first chapter of this dissertation is a background of freight transportation and its challenges. It starts with an introduction to freight demand increase and capacity of transportation infrastructure to accommodate the growing freight demand. This chapter continues with a literature review of projects and research on constructing freight pipeline systems in the U.S. and around the world. Finally, chapter one explains the projects and research that provide the basis for writing this dissertation.

Chapter two analyzes the design and operation of an intermodal freight terminal for the Port of Houston. This chapter starts with finding appropriate routes for designing freight pipelines from the Port of Houston. The goal of this study is to design the UFT system below existing highways without the cost and problems of land purchase. Two routes are suggested: the first route carries pallet-size loads from the Port of Houston to a distribution center outside Houston where trucks can pick up the loads. This suggested route will decrease the truck traffic in the congested downtown Houston and port area. The other route is a long-haul route that transfers shipping containers from Port of Houston to an inland port near Dallas. This route will be located mostly beneath IH-45 and will decrease the need for truck transportation between Houston and Dallas. After planning the routes, UFT design configuration is specified, including: vehicle design, gear system, tunnel specifications, and propulsion system. Afterwards, the operational attributes for each route such as headway, capacity, speed and flow will be analyzed.

Chapter three assesses the design and operation of an intermodal terminal for a freight pipeline transportation system. This terminal should be able to accommodate individual vehicles with short headways. In this chapter the terminal rail layout and circulation of UFT vehicles is illustrated and also, the operation of terminal, lifting equipment operation and loading/unloading process is analyzed. In chapter four, a UFT system for DFW Airport is designed to transfer the cargo from the airport cargo terminal to an intermodal terminal outside the airport protected zone. This system reduces the problems and concerns of truck traffic in the airport area and makes the airport more safe and environmental. This chapter starts with finding an appropriate location for the intermodal terminal and then depicts the system design configuration. The operation attributes of the UFT system and its intermodal terminal is determined later in the chapter.

Chapter five is a necessary part of the freight pipeline operation study. This chapter analyzes the mechanics and dynamics of the vehicle in the pipeline and identifies the affecting forces on the vehicle either in motion or stop. This chapter analyzes the aerodynamics of the vehicle based on the cruising speed and finds a relation between the UFT vehicle speed and its energy consumption. Also, the LIM specification is calculated based on the weight of the vehicle and its desired speed in the tunnel. The final chapter is dedicated to the conclusion and discussions about the designed freight pipeline systems in this dissertation and UFT systems in general. In this chapter the conclusion and lessons learnt from each chapter are presented and challenges for future works is identified.

Chapter 2. Schematic Design and Operational Analysis of Intermodal Underground Freight Transportation Systems with Application in Ports

2.1.Introduction

The demand for freight transportation is on the rise as a result of population growth, increase in the need for energy, and the expansion of global trade. Existing infrastructure for freight transportation seems inadequate for future growth, and new facilities are required to cover the deficiencies in cargo movement. Underground Freight Transportation (UFT) is a new mode of transportation that uses the space below the ground to carry cargo in individual vehicles in tubes and pipelines. Two short-haul and long-haul UFT systems with different load sizes are used to test and apply the results of this research. The findings of this research suggest that because of its light weight and minimal thickness, a Linear Induction Motor (LIM) is the most appropriate propulsion system for UFT. Besides, this research estimates that the energy consumption and power requirement of a LIM system is low. The energy consumption of LIM system is calculated as a function of UFT system operating speed. The results of this research can be applied in the design, operation and cost estimating of other UFT systems.

2.2. Research Objectives

The goal of this paper is to develop a new system for freight transportation which is, compared to other modes of transportation, more reliable, safe, and more environmentally friendly. This research provides schematic designs and operation equations for this new system. Introducing a new mode of transportation requires elaboration of the system design and adoption of realistic operational parameters. The secondary goal of this research is to provide a reference for the design and operation of

UFT systems. According to the literature review, an Underground Freight Transportation (UFT) system could play a significant role in making up some of the future capacity shortfall in the over-ground freight transportation system. This study proposes a long-haul and a short-haul UFT system, including schematic designs of geometric and operational subsystems.

The research starts with the identification of the components required for operation of the UFT system. A wide range of components from mechanical facilities to electronic control systems will be introduced. The design section will lead to presenting several design alternatives and system options. Afterwards, the research seeks to identify parameters required for operation of the UFT system. To make the research more practical, two congested freight transportation corridors in Texas will be selected as the case studies. The selection of these routes will help in detailing the design of a UFT system as well as specifying the operation parameters. The routes start at one of the main origins of cargo in Texas and will end at one of the demand centers in the state. The selection of a specific route, however, will not limit the application of this research as the results are expected to be applicable to any UFT route.

2.3. Planning the UFT Route

One of the main benefits of a UFT system is its ability to be constructed in the right-of-way of the existing highways. As such, the cost of land purchase can mostly be avoided in such a system with the exception of the land needed at the terminals. This ability is important because all other scenarios for increasing freight transportation capacity such as constructing a new railway or adding a truck lane, include an extensive land acquisition process. Purchase of land is one of the most challenging steps in any civil engineering project. This is not only due to the cost of the land itself, but also the legal issues and costs often associated with the land acquisition process for public projects. In fact, the land acquisition process for large-scale engineering projects may take several years to accomplish. Furthermore, right-of-way constraints may force many compromises that will affect the system configuration and route design. All in all, the UFT system should be constructed in the right-of-way of the existing highways. According to TxDOT, the most congested roadways in Texas in 2016 are IH-35 in Travis County and IH-45 in Harris County. These corridors also have the highest truck delays in Texas (TxDOT, 2016).

This study considers two routes: a short-haul route connecting the Port of Houston to a proposed intermodal satellite terminal near Houston and a long-haul route connecting the Port of Houston to a proposed intermodal inland port in Dallas. The short-haul route is 15 mile long and is designed to carry pallet size loads to the intermodal satellite terminal where trucks can pick up their load. The long-haul route is 250 miles long and starts at the Port of Houston. This UFT system delivers shipping containers to an intermodal inland port, south of Dallas. At the intermodal inland port, the UFT system can deliver loads to the existing rail system or a truck terminal. Figures 2.1 and 2.2 show the two short-haul and long-haul routes of the proposed UFT system. As shown on the maps, the UFT routes are designed to be constructed beneath existing highways in order to avoid land purchase cost and challenges.

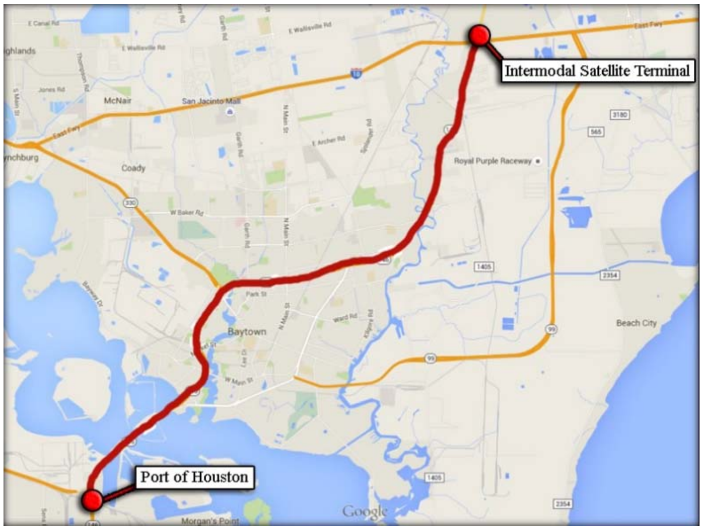


Figure 2.1 UFT Short-haul Route between Port of Houston and Intermodal Terminal

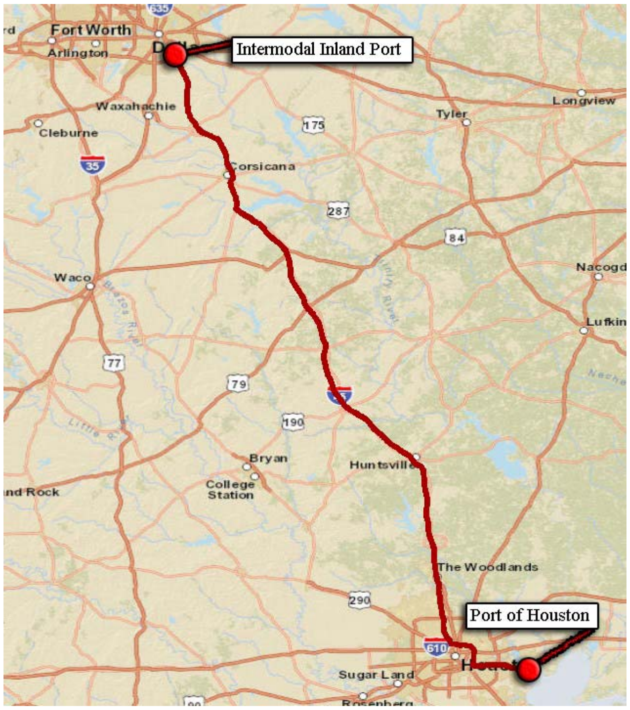


Figure 2.2 UFT Long-haul Route between Port of Houston and Dallas Inland Port

2.4. UFT System Design

An underground freight transportation system should include several components for the operation of the system. The following sections describe the key components necessary to consider in a UFT system design:

2.4.1 Load

With technical advances in the design of linear induction motors as well as tunnel boring machines (TBMs), UFT systems can carry large load sizes. This study considers two different sizes: the Standard shipping container and the Standard US pallet. The standard shipping container (ISO 668:2013 standard container), is 40 ft. long, 8 ft. wide, and 9.5 ft. high, and can accommodate 20 US pallets. Shipping containers can have a maximum gross weight of 68,000 lbs. A standard US pallet is 4 ft. long, 3.3 ft. wide, and 3.3 ft. high, and can have up to 4,600 lbs. gross weight. The shipping container size UFT system is most suitable for transportation of cargo to and from sea ports. This may be a short-haul line, for instance from a sea port to a satellite inland port, or from the port to a major destination city. The pallet size load is considered for transferring cargo in urban areas, from cargo terminals to warehouses or vice versa. The pallet size UFT system can also be utilized in a network connecting different cargo origins and destinations. This may include intermodal terminals, supermarkets, shopping malls, and post offices. Such a network can reduce truck traffic in urban areas and decrease noise and air pollution as well. Figures 2.3 shows the shape and size of each load type.

(a) Shipping Container

(b) US Pallet

Figure 2.3 Shape and Size of (a) Shipping Container and (b) US pallet

2.4.2 Tunnel

The tunnel is the underground space required for the transportation of freight. It can be cylindrical like a tube or rectangular like a culvert in cross section. While a cylindrical tube works best with Tunnel Boring Machines (TBM), the rectangular culvert may be used in rural areas where the cut-and-cover method for construction is more practical. Pipelines are mostly made of precast concrete pipes but in smaller sizes, steel pipes may also be used (Najafi, 2016). UFT pipelines may be single-track or dual-track. In routes with a high freight demand, dual-track tunnels may be used for transporting freight in both directions. Single-track tunnels are suitable for short haul distances and may be used in each direction based on a temporal schedule. Single-track tunnels also may be a part of a UFT network for transferring freight from an intermodal terminal to a distribution center or a supermarket.

2.4.3 Vehicles

Vehicles for transportation of freight can be considered as covered capsules or flatbed gondolas. Capsules are typically metallic with a hatch door at one end of the vehicle for placement or retrieval of the cargo. Covered vehicles are recommended for unboxed loads like pallets to prevent load spillage as well as to provide climate control where needed (e.g. transport of medicines or perishable foods) (Najafi, 2016). Covered capsules are not recommended for the shipping containers because load spillage seems unlikely in closed shipping containers, and the containers themselves may be climate-controlled if needed. Therefore, an open flat-bed gondola with a rectangular cross-section can be considered for shipping containers. The schematic design of UFT vehicles show that with the additional front and rear overhangs required for operational purposes, the overall vehicle length for the shipping container is 49 ft. and for the pallet is 5 ft.

2.4.4 Gear System

Three gear systems are studied to design the most reliable and cost-effective running gear system for the proposed UFT system. The studied gear systems include: Maglev (Magnetic Levitation), rubber tires, and steel wheel and rail systems. This study compares these systems based on ride quality, material durability, required maintenance, and capital and operating costs. Rubber tire systems have high traction that makes them more desirable for sloped routes. They offer smoother ride quality and they are able to stop or reach the highest design speed in shorter time than the regular steel wheel and rail systems. However, they have high energy consumption due to high tire friction and high maintenance requirements (Roop, 2002). Although the capital cost of rubber tire systems are less than the other two systems, high maintenance and reliability issues associated with these systems (such as tire blow-outs) make them unsuitable for the proposed UFT system.

The steel wheel and rail system is more reliable than the rubber tire system and has lower maintenance costs. Furthermore, the environmental pollution and energy consumption of steel wheels and rail is lower than the rubber tire system. The steel wheel and rail's braking and sliding problem can be solved when it is used in combination with a LIM (Linear Induction Motors) propulsion system (Vollenwyder, 2006). In a LIM system, the steel wheels only carry the vehicle weight. The acceleration/deceleration will be generated through the induction force. Maglev systems are among the most recent running systems used to move trains. These systems levitate vehicles on guideways using electromagnetic force. The absence of a wheel in these systems offers higher ride quality, lower maintenance, and higher speeds compared to rubber tire and steel wheel and rail systems (Lee, 2006). Nevertheless, the lack of experience and substantial capital cost of Maglev systems makes them unsuitable for the proposed UFT system.

According to the literature review, existing freight pipelines use either rubber or steel wheels (Liu, 2000). Although rubber tires are used in a few freight pipeline systems, it is recommended to use steel wheels in UFT systems. Comparing all the functional and economic aspects of the studied running gear systems, the steel wheel and rail with LIM propulsion is identified as the most suitable gear system for the proposed DFW UFT system. Regarding the steel rail and wheel configuration, two common standards for track gauges in the U.S. exist: standard gauge and narrow gauge. It is recommended to use one of these common gauges for UFT systems as the tools, tracks, and equipment for these gauges are readily available in the market. As such, using common gauges make the installation and maintenance costs lower. The standard rail gauge size is 4 ft. and 8.5 in. wide, which is suitable for a standard shipping container UFT system. The width of narrow rail gauge is 3 ft. and 6 in. or 3 ft., which is suitable for a pallet-size UFT system.

2.4.5 Propulsion System

UFT systems can be designed to be more environmentally-friendly than other modes of freight transportation. Hence, it is necessary to use a propulsion system that has the lowest pollution, while delivering enough force for propulsion of vehicles. Generally, two different propulsion systems are used in underground freight pipelines, pressure-propelled pneumatic systems or electrical motors. Pneumatic Capsule Pipelines (PCP) typically use a negative pressure system (suction) or positive pressure system (Blowing) but these systems have serious limitations with respect to the size and length of the UFT systems (Egbunike, 2011). Linear electric motors are a general term for non-adhesive propulsion systems that generate linear movement through induction or magnetic thrust. This technology is newer compared to rotary motors, but it is well developed and has been used in different transportation systems worldwide. Utilization of a LIM (Linear Induction Motor) in underground freight transportation systems is advantageous both economically and technically (Thornton, 2009). First, the narrow height of a LIM system reduces the vehicle height and subsequently the pipeline diameter. This in turn reduces the construction costs. Also, the light weight of the LIM decreases the weight of the vehicles, which results in lower energy consumption.

2.4.6 Access Shafts and Air Vents

The movement of vehicles in the tunnel produces an air drag force which is a result of the difference in air pressure in the front and back of the vehicle. Besides, the vehicles travel and power consumption in LIM produces heat. In order to balance the air pressure along the tunnel and ventilation of the heat from the vehicles' movement, air vents must be provided at regular distances along the UFT tunnel. The tunnel requires shafts for access in case of emergency and to perform maintenance. Although UFT systems are designed to be automatic and reliable, every transportation system requires periodic checks and maintenance. The access can be provided through a lift or using a manhole. The distance between the access shafts depends on the system size and capacity.

Figures 2.4 and 2.5 respectively represent the schematic design for the standard US pallet and standard shipping container UFT systems using the components discussed in this section. Figure 2.6 shows the schematic longitudinal design of the shipping container UFT system.

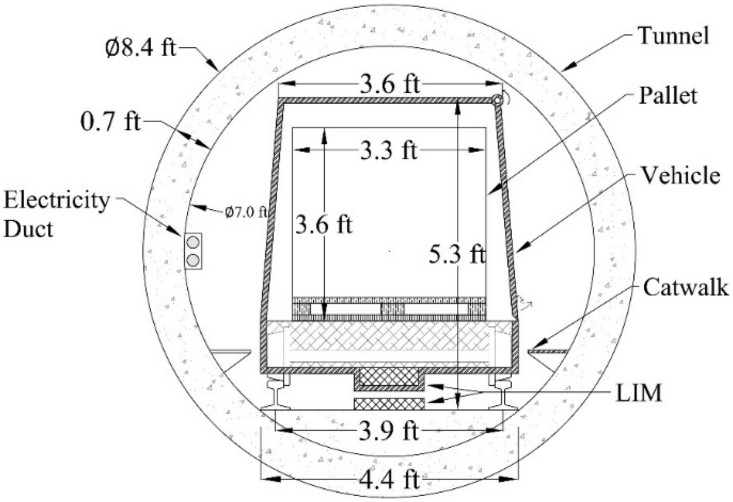


Figure 2.4 Schematic Design of the Standard US Pallet UFT System

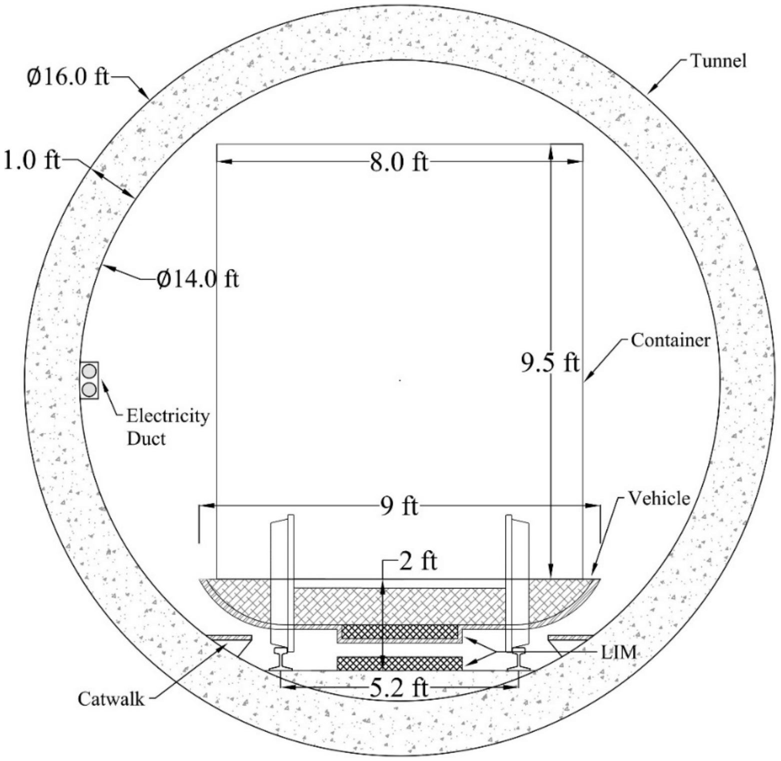


Figure 2.5 Schematic Design of the Standard Shipping Container UFT System

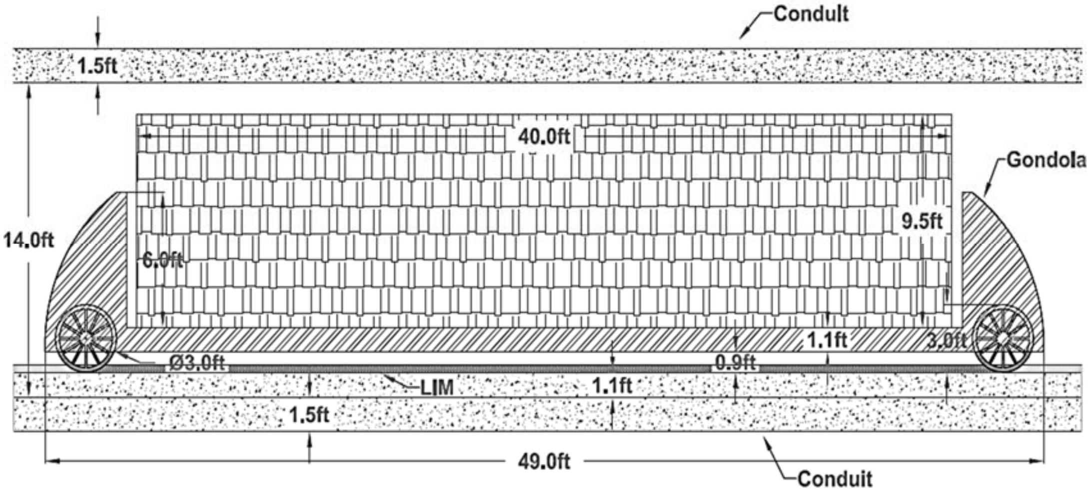


Figure 2.6 Schematic Longitudinal Design of the Shipping Container UFT System

2.5. UFT System Operation

The goal of this section is to develop a mathematical relation between headway, flow, capacity and speed of a UFT system. The findings are then applied to the proposed short-haul and long-haul lines. The aim is to determine the relation among operating speed, minimum safe headway, desired container flows, and number of vehicles needed in the UFT system. Variables that significantly impact the operation of a UFT system include operating headway, loading/unloading time, desired speed, and route length. While a small headway may raise safety concerns, a large headway will decrease the system efficiency. In addition, the capacity of a UFT system in terms of containers delivered per day should be sufficiently high to justify the construction and operation of the system.

2.5.1 Optimum Speed

The UFT system is designed to use an electric linear induction motor as its propulsion system. As is the case with other energy sources, the energy consumption in LIM systems has a direct relation to the operating speeds and acceleration rates. Keeping the operating speed of the UFT system low will lead to lower power requirements and operating costs. A lower speed also has benefits regarding the rail track, vehicle, and the overall pipeline system depreciation. The difference between freight and passenger transportation is that freight transportation should be reliable and timely rather than fast. The UFT speed should however be competitive with other competing modes (truck and rail) speed. According to the Federal Highway Administration (FHWA), the average truck speed on Interstate Highway 45 (IH-45) between Houston and Dallas is 54 mph (Federal Highway Administration, 2016). However, the 54-mph speed is the average running speed for trucks and does not account for stops, re-fueling, dinning, being checked at weight stations, etc. Therefore, the average overall truck speeds are expected to be much lower than 54 mph.

The freight rail system connecting Houston to the DFW metropolitan area is owned and operated by the Union Pacific Railroad Company. Based on the daily reports of rail movement on the company website, the average speed in this system is between 30 to 33 mph, which is even lower than truck operating speeds (Union Pacific Railroad, 2016). A comparison of these data indicates that the operating speed of 45 mph is considered as the proper speed for the UFT system. This speed is high enough to be comparable to the overall speed of trucks and freight trains but low enough to minimize energy consumption.

2.5.2 Minimum Headway

Several factors influence the choice of headway in a UFT system. Two types of UFT headways can be defined: the minimum headway and the operating headway. Safety concerns and propulsion system restrictions provide a basis for determining the minimum headway. The operating headway, on the other hand, is defined based on the desired system flow and demand, which could be lower than the system capacity. The minimum headway (h_{min}) should be determined so that it meets the propulsion system requirements as well as prevent collisions between successive vehicles. This suggests that the headway between two successive vehicles should be large enough for the first vehicle to reach the highest operating speed while providing enough time for the safe stop of the second vehicle. The time required to travel the length of a vehicle should also be considered in this computation.

The functional relation for the required minimum headway based on the above considerations is represented in equation 2.1.

$$h_{min} = \frac{l}{1.47\,v} + 1.47v\left(\frac{1}{a} + \frac{1}{d}\right) \qquad \text{Eq. 2.1}$$

where:

h_{min} = minimum headway between vehicles (sec),

l = length of the vehicle (ft.),

v = running speed (mph),

a = acceleration rate (ft/sec^2), and

d = deceleration rate (ft/sec^2).

Like the cruising speed, acceleration and deceleration rate is also an important variable in energy consumption. A high acceleration/deceleration rate will increase energy consumption, in most cases without a commensurate operational benefit. An acceleration/deceleration rate of 5 ft/sec^2 is considered for the shipping container UFT system. The pallet size UFT system is recommended to have acceleration/deceleration rate of 10 ft/sec^2 as the pallet size vehicle is shorter in length and lighter in weight. According to equation 2.1, for the shipping container (Long-haul) system, considering the length of 49 ft, an operating speed of 45 mph, and acceleration/deceleration rate of 5 ft./sec^2, the minimum headway is 28 sec. For the pallet (short haul) system with length of 5 ft and acceleration/deceleration rate of 10 ft/sec^2, the minimum headway is 14 seconds.

2.5.3 System Capacity

The system capacity is defined as the maximum number of containers that the UFT system can deliver in a day. Capacity can also be considered as the maximum flow of vehicles. Based on the definition, the system capacity is directly affected by the minimum headway of the system and facility operating hours.

Equation 2.2 shows the relation between the minimum headway, working hours per day, and the system capacity.

$$C = 3600 \frac{T}{h_{min}} \qquad \text{Eq. 2.2}$$

Where:

h_{min} = minimum headway (sec),

T = working hours (hrs/day), and

C = system capacity (vehicles/day/direction).

Based on the estimated minimum headway of shipping container system (28 seconds) and 24 hours operation, the system capacity is estimated to be 3,085 vehicles/day/direction. For the pallet system with minimum headway of 14 seconds and 24 hour operation, the capacity is 6171 vehicles/day/direction.

2.5.4 Fleet size

It is necessary to determine the number of vehicles in use when the system is operating at capacity (at minimum headway). The fleet size shows the number of vehicles that should be built for the UFT system and plays an important role in estimating costs of UFT system construction. When the UFT system is handling flows lower than capacity, not all vehicles will be in use. The excess vehicles can either be on stand-by in each terminal's layover sections or continue to circulate in the line with no payload. The former option may require a larger terminal area while the latter option would result in higher energy consumption.

The required number of vehicles in use depends on the system length, speed, minimum headway, and follows equation 2.3:

$$N_g = 7200\left(\frac{L}{v \cdot h_{min}}\right) + 1.47\left(\frac{v}{h_{min}}\right)\left(\frac{1}{a} + \frac{1}{d}\right) \qquad \text{Eq. 2.3}$$

Where:

N_g = Number of vehicles in use,

h_{min} = Minimum headway (sec),

L = Total length of the line (miles),

v = Running speed (mph),

a = Acceleration rate (ft/sec^2), and

d = Deceleration rate (ft/sec^2).

Considering the acceleration/deceleration rate of 5 ft/sec^2, running speed of 45 mph, and the route length of 250 miles, the fleet size of the shipping container system is 1429 vehicles. For the short-haul system with 15 miles route length and acceleration/deceleration of 10 ft/sec^2, the total number of vehicles required is 172 vehicles.

2.6. Conclusion

The increase in freight transportation in Texas as well as many other parts of the US is inevitable. This increase will have a profound impact on the highway and rail systems. Therefore, increasing the capacity of the freight transportation system is imperative. Underground freight transportation can play an important role in intermodal freight mobility in Texas. This research developed schematic designs for two different load sizes: 40 ft. shipping containers and Standard US pallets. Two congested corridors were selected for estimation of UFT operational attributes. A short-haul route connecting port of Houston to an intermodal satellite terminal and a long-haul route connecting Port of Houston to an intermodal inland port in south of Dallas.

The operational parameters for each of the two routes for standard shipping container and pallet systems are summarized in Table 2.1. The developed equations for operation of UFT system is applicable to all UFT systems regardless of route length or load size. The findings of this research can be advantageous in the planning, cost-benefit analysis, cost estimation, and operation design of UFT systems. The information from design and operation of UFT system can be used for estimation of the energy and propulsion system requirement. Moreover, the study of capacity of the UFT system and its comparison with rail or truck system requires the UFT operation information.

Table 2.1 Summary of Operational Attributes of Each UFT System

Route	**Port of Houston - Dallas**	**Port of Houston - Satellite Terminal**
Hauling Length	long-haul	Short-haul
Route Length (miles)	250	15
Route Type	Urban-Rural	Urban
Load Type	Shipping Container	US Pallet
Load Size	8'Wx9.5'Hx40'L	3.3'Wx3.3'Hx4'L
Load Weight (lb.)	68,000	4,600
Vehicle Length (ft.)	49	5
Vehicle Type	Flatbed Gondola	Covered Capsule
Gear System	Steel Wheel and Rail	Steel Wheel and Rail
Propulsion System	Linear Induction Motor	Linear Induction Motor
Speed (mph)	45	45
Accel/Deccel Rate (ft/sec^2)	5	10
Min Headway (sec)	28	14
Capacity (veh./day/direction)	3,085	6,171
Fleet Size (veh)	1,429	172

Chapter 3. Intermodal Terminal Design and Operation for individual Autonomous Vehicles

3.1. Introduction

This chapter investigates the design and operation of an intermodal terminal for anUnderground Freight Transportation (UFT) system. UFT is considered to be new mode of freight transportation that uses pipelines for transporting freight between two intermodal terminals. The load size and route length of the UFT system can be variable depending on the purpose and specifications of the project. In this paper two sizes of loads and two route lengths are considered to show that the terminal design and operation are independent from route length and load size. Each UFT route starts at the Port of Houston where shipping container or pallet size loads will be delivered to the UFT system. The short-haul route ends at a proposed intermodal satellite terminal outside Houston and the long-haul route terminates in a proposed intermodal inland port in Dallas. This paper develops equations to estimate the operational attributes of the UFT intermodal terminal. These attributes include operational headway, system flow, fleet size, and number of handlers/forklifts required in operation of the terminal. Based on the terminal operation requirements, a typical design for a UFT intermodal terminal is presented. In addition, the loading/unloading process and the freight circulation scheme are discussed. Although, this schematic terminal design and operation are for shipping container loads, but the same concept can be applied to smaller scale loads such as pallets.

3.2.Research Objectives

The goal of this research is to represent schematic designs for Underground Freight Transportation (UFT) intermodal terminals and elaborate the loading/unloading process. The research tries to calculate operational attributes prevailing in UFT terminals and scrutinizes the freight circulation in the terminal area. The freight pipeline is a class of autonomous transportation systems in which close-fitting capsules or flat-bed gondolas carry freight through pipelines or tunnels between terminals. The objective is to present a schematic planning and design process for the freight pipeline terminals so as to be a reference for future UFT system designs regardless of location, size, and depth. Typical UFT system components include the transferable loads, tunnel system, vehicles (capsules or gondolas), gear system, propulsion system, terminal design and intermodal load transfer systems.

This study covers the UFT operational attributes necessary for running the UFT terminals. Corresponding equations are developed to estimate the required headways, number of vehicles, and loading/unloading handlers/forklifts as a function of the container flow per day and working hours. According to the operational attributes and load circulation in the terminal, schematic designs for the UFT intermodal terminal are created. These typical designs include dimensions in terminal area, location of main lines, bypass lines, layover and maintenance lines, loading/unloading platforms, handlers/forklifts, container stack yards, and intermodal service roads.

3.3. UFT System Components

3.3.1 Route

For the purpose of this research two routes are considered, a short-haul route and a long-haul route. The short-haul route connects the Port of Houston to a proposed intermodal satellite terminal near Houston and is 15 miles long. The long-haul route connects the Port of Houston to a proposed intermodal inland port in Dallas and is 250 mile long. In both intermodal terminals, trucks can access the terminal to load or unload shipping containers.

3.3.2 Load

Two different loads are considered for the study of the UFT system, standard shipping containers and standard US pallet. A shipping container is 40 ft. long, 8 ft. wide, and 9.5 ft. high, and can accommodate 20 US pallets. Shipping containers can have a maximum gross weight of 68,000 lbs. US pallets are 4 ft. long, 3.3 ft. wide, and 3.3 ft. high, and can have up to 4,600 lbs. gross weight. The shipping container size UFT system is most suitable for transportation of cargo from and to sea ports. The pallet size load is considered for transferring loads in urban areas, from cargo terminals to warehouses or vice versa

3.3.3 Vehicle

Vehicles for transportation of freight can be considered as covered capsules or flatbed gondolas. Capsules are typically metallic with a hatch door at one end for placement or retrieval of the cargo. Covered capsules are recommended for unboxed loads like pallets to prevent load spillage. Covered capsules are not recommended for the shipping containers as there is little chance of load spillage in closed shipping containers.

3.3.4 Tunnel

The tunnel is the underground space required for the transportation of freight. tunnel in cross section can be cylindrical like a pipeline or rectangular like a culvert. UFT tunnels may be single-track or dual-track. In routes with a high freight demand, dual-track tunnels may be used for transporting freight in both directions. Single-track tunnels are suitable for short haul distances and may be used in each direction based on a time schedule. Figures 3.1 and 3.2 represent the schematic design for the standard US pallet and standard shipping container UFT systems, respectively.

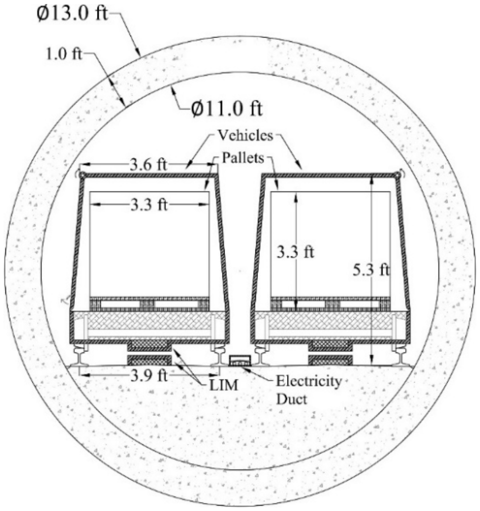


Figure 3.1 Schematic Design of Pallet-Size Dual-Track Freight Pipeline

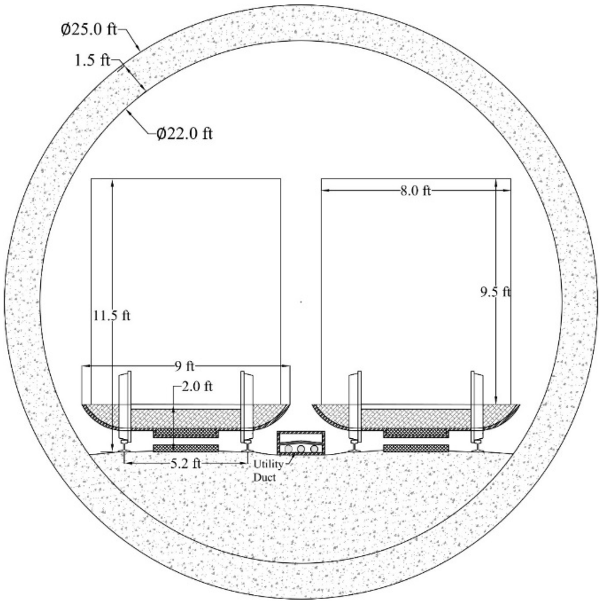


Figure 3.2 Schematic Design of Container-Size Dual-Track Freight Pipeline

3.3.5 Gear System

Existing freight pipelines use either rubber or steel wheels. Although rubber tires are used in a few freight pipeline systems, it is recommended to use steel wheels in UFT systems as they are less polluting and require less maintenance. Comparing the functional and economic aspects of the running gear systems, the steel wheel and rail with LIM propulsion is identified as the most suitable gear system for the proposed UFT system.

3.3.6 Propulsion System

Linear electric motor is a general term for a non-adhesive propulsion system which generate linear movement through induction or magnetic thrust. Utilization of LIM (Linear Induction Motor) in underground freight transportation systems is advantageous both economically and operationally. First, the narrow height of a LIM system reduces the vehicle height and subsequently the tunnel diameter. This in turn reduces the construction costs (Kaye, 2004). Also, the light weight of LIM decreases the weight of vehicles, which results in lower energy consumption.

3.3.7 Handler/Forklift

Handlers and forklifts are one of the most essential and costly components of a UFT terminal. Special machines are needed in terminal area for loading/unloading of UFT vehicles and trucks. Container handlers are suggested to be used in terminal area. These handles are fast and have a high level of maneuverability. Handlers can stack containers up to six levels and have a small turning radius (Toyota Industrial Equipements, 2017). These handlers should be able to carry containers up to 35 ton weight. Pallet forklifts should carry lighter weights up to five tons. In pallet UFT system, electric forklifts which have less environmental pollution may be used. Figure 3.3 shows samples of handlers and forklifts for the terminal area.


(a) Shipping Container Handler (b) Pallet Forklift

Figure 3.3 Suggested (a) Electric Container Handler and (b) Electric Pallet Forklifts.

3.4. Terminal Operation

3.4.1 Capacity and Headway

The operating headway for the UFT system is primarily influenced by the system flow rate, the number of containers to be delivered in a day and the working hours per day at the origin and destination. The operational headway can be calculated using equation 3.1:

$$h_{opr} = 3600\ \frac{T}{Q} \qquad \text{Eq. } 3.1$$

where:

h_{opr}= operating headway (secs),

T= working hours (hrs/day), and

Q = System flow (vehicles/day).

Table 3.1 shows the operating headway based on the vehicle flow in the system based on 24 hours a day operation. Figure 3.4 shows the relation between flow and operational headway in a UFT system.

Table 3.1 The Relation Between Flow Rates (Q) and Headways (h_{opr})

Q (veh/day)	$h_{(opr)}$ (Secs)
2,000	43
2,500	35
3,000	29
3,500	25
4,000	22
4500	19
5000	17
5500	16
6000	14

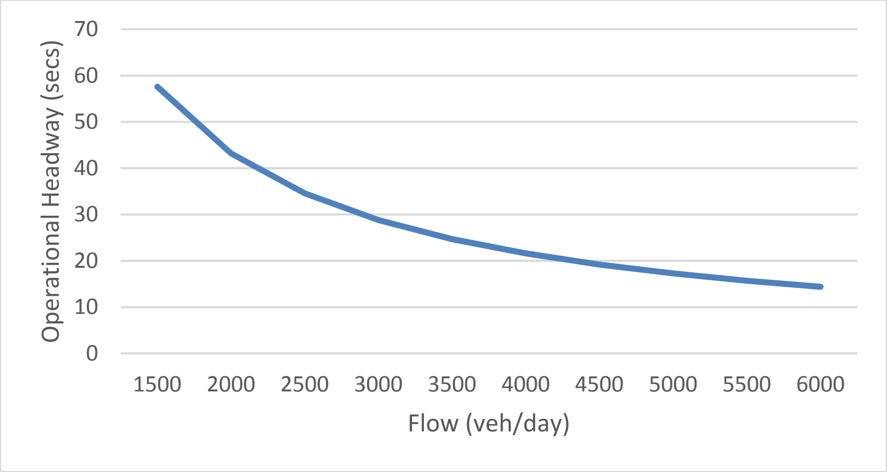


Figure 3.4 The Relation Between Flow and Operational Headways

3.4.2 Vehicles in Use

In the operation of the UFT system, it is necessary to know the number of vehicles in use when the system is operating. When the UFT system is handling flows lower than capacity, not all vehicles will be in use. The excess vehicles can be either on stand-by in each terminal's layover section or continue to circulate in the line with no payload. The required number of vehicles depends on the system length, speed, and operational headway, as in equation 3.2:

$$N_v = 7200\left(\frac{L}{v \cdot h_{opr}}\right) + 1.47\left(\frac{v}{h_{opr}}\right)\left(\frac{1}{a} + \frac{1}{d}\right) \qquad \text{Eq. 3.2}$$

where:

N_v = number of vehicles in use,

h_{opr} = operating headway (secs),

L = total length of the route (miles),

v = running speed (mph),

a = acceleration rate (ft/sec^2), and

d = deceleration rate (ft/sec^2).

Equation 3.2 yields the required number of vehicles in the UFT system in both directions based on operational headways. Table 3.2 provides the required number of vehicles in two short-haul (15 miles) and long-haul routes (250 miles). For calculation purposes, acceleration and deceleration rates are assumed to be 10 ft/sec^2 and the speed is assumed to be 45 mph. Figure 3.5 also shows the required vehicles in the UFT system according to the headway.

Table 3.2 The Relation Between Headway and Number of Vehicles

Route	**Long-haul**	**Short-haul**
Length (mile)	**250**	**15**
h_{opr} (seconds)	Number of vehicles	Number of vehicles
15	2,668	161
20	2,001	121
25	1,601	97
30	1,334	80

35	1,143	69
40	1000	60
45	889	54

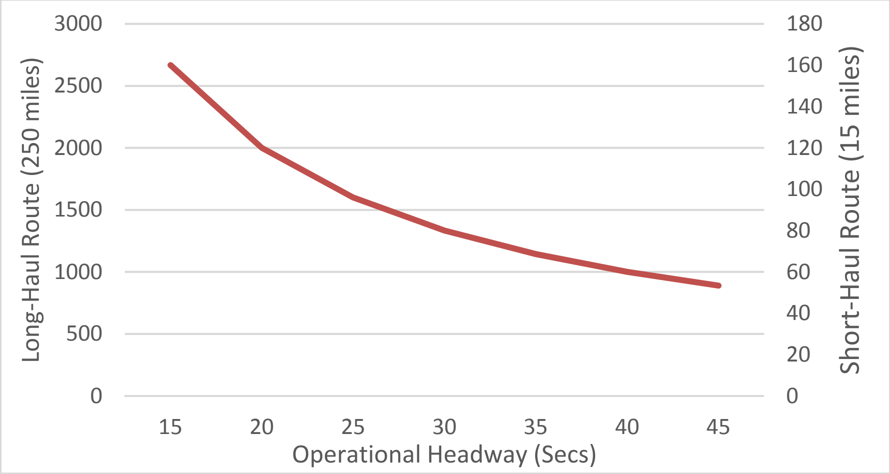


Figure 3.5 Vehicles needed in each UFT system

3.4.3 Loading/Unloading Platforms

Terminals should have multiple loading/unloading platforms. In these platforms handlers or forklifts unload full UFT vehicles and load empty UFT vehicles. The time required for handlers to load or unload a shipping container also determines the number of platforms in each loading/unloading section of the terminal. For the proper function of terminal and balance of loading/unloading process, the number of loading and unloading should be equal. Equation 3.3 shows the relation between flow, UFT system working hours per day, the loading/unloading time, and the number of loading and unloading platforms:

$$N_p = \frac{Q.t}{3600T} \qquad \text{Eq. 3.3}$$

where:

N_p = number of loading/unloading platforms,

t = loading/unloading time (sec),

T = working hours (hrs/day), and

Q = system flow (vehicles/day).

This number is equal to the number of platforms needed in each loading and unloading section of the terminal. For example, if the process of loading/unloading a shipping container with handlers takes 90 seconds and the UFT system has a capacity of 3000 vehicles per day, three pairs of loading/ unloading platforms are needed. For a pallet-size UFT system with a 60 seconds loading/unloading time with a lift and 6000 vehicles per day capacity, the number of required platforms is four.

3.4.4 Handlers and Forklifts

Handlers are used for both loading and unloading the shipping containers as well as for stacking the shipping containers in the stacking yard and for loading/unloading trucks. Forklifts are used for lifting loads in pallet size UFT systems. The operational characteristics of handlers/forklifts significantly influence the UFT system capacity. A UFT system with a higher capacity requires a higher number of handlers to accommodate arriving or departing freight.

For each loading/unloading platform a total of 4 handler/forklifts are needed in the UFT terminal, two for loading and unloading the UFT vehicles to the stacking yard and two for loading and unloading trucks from the stacking yard. If we denote N_t to be the total number of handlers required in the system, then $N_t = 4N_P$. A number of additional (backup) handlers will also be needed in case of emergency or breakdown of the operating handlers. It is reasonable to consider two additional handlers for each section of the terminal (loading and unloading sides) as backups. As a result, the total number of handlers required in the UFT terminal can be calculated as in equation 3.4:

$N_t = 4(N_p + 1)$ Eq. 3.4

where:

N_p = number of loading and unloading paired platforms and

N_t = total number of handlers/forklifts required.

For example, in a terminal with three loading/unloading platforms, a total of 16 handlers is required. Table 3.3 shows the number of loading/unloading platforms and handlers/forklifts required in the UFT terminal in relation to the capacity of the UFT system.

Table 3.3 The Relation Between Flow Rates and Number of Forklifts/Handlers

UFT System	**Capacity (veh/day)**	**Number of platforms (N_p)**	**Number of Handlers/Forklifts (N_t)**
Pallet-size	3,000	3	16
Shipping Container	6,000	4	20

3.4.5 Terminal Design

The scope of this section is to develop a schematic design for the UFT system terminals. The terminal design specifications include rail facility design and layout, freight handling, highway access, planning and environmental considerations, and project timescales (Network Rail, 2016). The development of individual freight terminals demands a detailed approach for freight flows, handling processes, equipment selection, the role of information communication technologies (ICTs) in freight transport, and the operational and control rules. Therefore, the design and operational analysis of these processes are significant components in providing a state-of-the-art functional design (2016).

As mentioned, the first step in this part would be line facility design and layout. A schematic terminal design plan has been developed which includes main lines, underpass lines, bypass shunts, loading/unloading platforms, truck service roads, handler locations, land-side transfer areas, and container stacking yards. A key component of the UFT terminal is the loading and unloading platforms. A total of three loading/unloading platform pairs are sufficient for UFT system with capacity of 3000 vehicles per day. If a higher capacity UFT system is needed, the number of platforms could be increased to handle additional container flows.

Figure 3.6 shows a schematic layout of a typical UFT terminal for standard shipping containers. As vehicles arrive, they are directed to the first available unloading platform. Bypass shunts are designed to alleviate queueing of arriving vehicles during the peak time. Unloading the freight on each platform by using a handler is estimated to take about 90 seconds. In turn, the minimum headway between consecutive vehicles could be as low as 30 seconds. Therefore, there is a potential for a traffic back-up without bypass shunts to allow vehicles to continue downstream of the track to the next available platform.

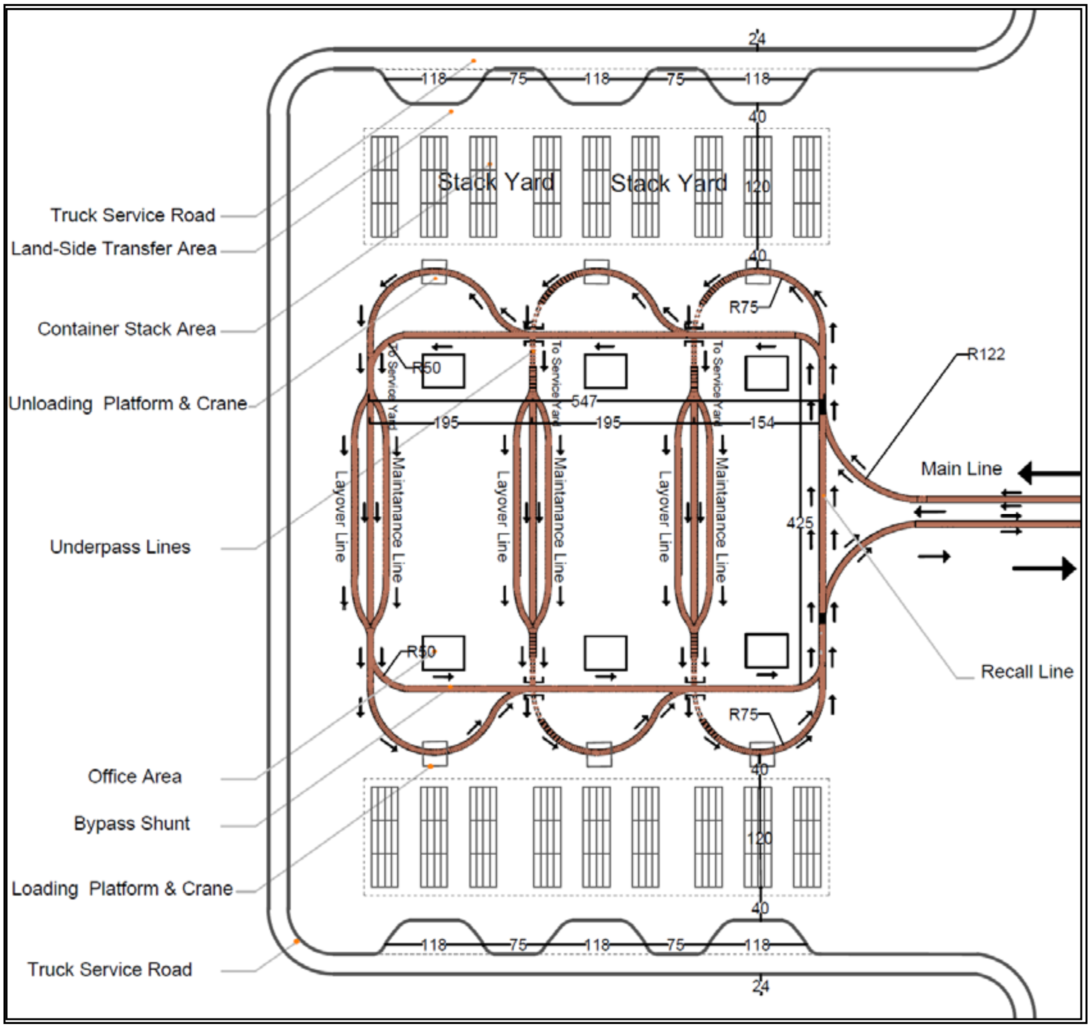


Figure 3.6 Schematic Design of UFT terminal for Shipping Container Loads.

After unloading their freight, vehicles are directed beyond the loading platform through the underpass lines. Underpass lines pass beneath the bypass shunts and are designed with an approximate 20% grade. They direct the vehicles to the loading platforms or, if need be, to the layover and maintenance lines for service or repairs. Layover lines and maintenance lines run parallel to the main line to allow vehicles to return to the main line when needed. Vehicles then pass underneath a second bypass shunt and proceed to the outgoing loading platform to be loaded with outbound freight and be directed to the outgoing main lines. Although this typical terminal design is for shipping container size loads, the same concept can be used for pallet size loads in a smaller scale with four loading/unloading platforms. Figure 3.7 is a three-dimensional model of a UFT terminal and circulation of cargo and trucks in the terminal.

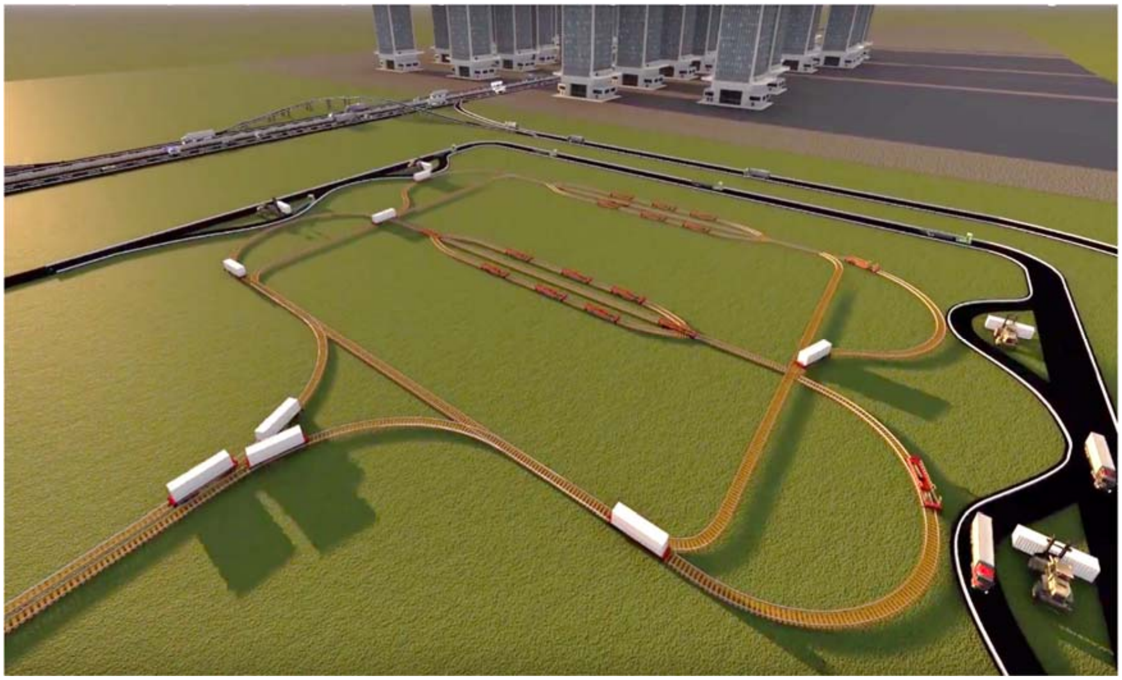


Figure 3.7 Three-Dimensional Model of UFT Terminal and Cargo/Truck Circulation.

3.4.6 Required Terminal Areas

The terminal area calculations entail required areas for handler operations, stack yards, truck access, service yard, and vehicle storage and parking. For the shipping container terminals, it has a constant value (56,000 sq. yd.) for the first pair of loading/unloading platforms, and a variable section for each additional pair of loading/unloading platforms, as represented in equation 3.5:

$A = 56{,}000 + 24{,}000(N_P - 1)$ Eq. 3.5

where:

A = total terminal area (sq. yd.), and

N_p = number of loading/unloading platforms.

The respective terminal area calculations for pallet system is given in by Equations 3.6.

$A = 12{,}000 + 10{,}000(N_P - 1)$ Eq. 3.6

Table 3.4 presents the resulting total number of loading/unloading platforms for each UFT system, the total terminal area and the terminal stacking area. For the shipping container size, eq. 3.5 yields a total terminal area of 104,000 sq. yds. (21.5 acres) for the Shipping container UFT line. The respective area size for pallet terminal is 42,000 sq. yds (Eq. 3.6), respectively. These estimates are based on number of loading/unloading platforms of each UFT systems.

Table 3.4 Required Terminal Area for Each UFT System

Freight Type	**Number of Loading/ Unloading Platforms**	**Total Terminal Area (sq. yd.)**	**Stacking Area (sq. yd.)**
Standard Shipping Container	3	104,000 (21.5 acres)	33,000 (6.8 acres)
Pallet	4	42,000 (8.7 acres)	7,000 (1.5 acres)

3.5.Conclusion

In this paper a schematic design for the intermodal terminal of a UFT system is presented and the necessary parameters for its operation are calculated. UFT system is a new mode of freight transportation that needs design standards and operational specifications. This paper has aimed at developing operational attributes and presenting a typical design for the intermodal terminal of a UFT system. The proposed terminal design can be used for different UFT systems and its overall plot and operational configuration can be tailored for either long-haul or short-haul systems. Regardless of the size and length of the UFT system, developed equations in this paper establish the relation between vehicles headway, UFT system capacity, and number of vehicles circulating in the system. In addition, the relation between headway, number of loading/unloading platforms and number forklifts/handlers in the terminal are calculated.

The design of the terminal is based on the required number of loading/unloading platforms. For each platform, bypass shunts and underpass lanes are proposed and designed. Since the headway is smaller than the loading/unloading time, multiple platforms are required. The unloaded freight can be kept in stacking yard and empty vehicles can stop in layover lines. The terminal is circled by a highway and trucks have direct access to the stacking yard. On one side of terminal trucks unload their freight and on the other side, they pick up their loads. For each loading/unloading platform, at least four forklifts/handlers are needed.

Each proposed route has two end terminals (no intermediate terminals). At each terminal, there are a number of loading/unloading platforms. Forklifts and handlers are required at each platform for loading and unloading the containers and pallets. For each platform, at least two forklifts/handlers are needed; one to load/unload vehicles and to haul the containers to the stacking yard, and the other to load/unload the trucks. In each terminal, a total of four additional handlers/forklifts are recommended for backup. Table 3.5 shows the parameters related to handlers/forklifts in terminals for each of the both freight types.

Table 3.5 Handler/Forklift Specifications and Operational Parameters

Attributes	Container	Pallet
Load weight (U.S. tons)	34	2.3
Min load/unload time (sec)	90	60
System capacity (vehs/day/direction)	2,880	4,320
Number of platforms	3	4
Number of forklifts	N/A	20
Number of handlers	16	N/A
Area (sq. yd.)	104,000	42,000
Stacking Area (sq. yd.)	33,000	7,000

Chapter 4. Application of Short-Haul Autonomous Underground Freight Transportation Systems to Large Airports

4.1. Introduction

The Dallas-Fort Worth International Airport handles about 600,000 metric tons of cargo annually. These shipments are currently transported by trucks from the airport cargo terminals. An underground freight transportation (UFT) system has the potential to substantially reduce the truck traffic within the DFW Airport area and thus improve safety, efficiency, and air quality. The main reason for designing a UFT system in the DFW Airport is security vulnerability, when trucks drive under or near active runways and taxiways and may have hazardous or explosive cargo. The proposed UFT system is expected to reduce the number of trucks on airport grounds and the airport access roadways, thus enhancing both the roadway access capacity and safety as well as reducing adverse environmental impacts such as emissions and noise. The objective of this paper is to examine the feasibility of underground short-haul freight pipelines to a large airport such as Dallas-Fort Worth International Airport. The proposed short-haul UFT system transports standard air freight crates between an airport cargo terminal and a distribution center off the secured airport grounds. The DFW Airport UFT system design includes planning level configurations of the tracks, vehicle, propulsion system, end-point terminals, and loading/unloading mechanisms at those terminals. Operational attributes such as speeds, headways, loading/unloading times, and line capacities are also determined.

4.2. Research Objective

The objective of this chapter is to design a short-haul underground freight transportation (UFT) system to be applied to a large airport and investigate the operational attributes of such system. In order to better understand parameters used in design and operation of the UFT pipeline, Dallas-Fort Worth (DFW) International Airport is considered for application of the UFT system. Using realistic parameters from DFW Airport helps in better understanding of system components, feasible design alternatives, and operational attributes. The proposed UFT line transports standard air freight crates between the cargo terminal and a distribution center off the secured airport grounds via an underground pipeline system. The secured airport grounds, also called Airport Operations Area (AOA), refer to the area of the airport bounded by a fence to/from which access is restricted (DFW Airport, 2011). The main reason for selecting a distribution center off the AOA is security vulnerability when trucks drive under or near active runways and taxiways and may have hazardous or explosive cargo. Also, regarding safety issues, an off-airport distribution center helps to reduce the percentage of trucks in the mix of the traffic to/from airport terminals. Reducing the truck traffic in the airport area also enhances the environmental quality of the airport specifically noise and air pollution.

Most studies about freight pipeline are concentrated on the economic feasibility of such systems or construction of the tunnels. In this paper, the potential origin-destination points within and around the airport are identified for the proposed UFT pipeline. The planning-level configuration of the system including the capsule size, the tunnel dimensions, the tracks, the end terminals, and the cargo storage and intermodal cargo handling are designed. Moreover, operational attributes for the system are addressed as well including running gear systems, power requirements, operational speeds and headways, loading/unloading times, and associated line capacities.

The proposed UFT system is believed to substantially reduce the number of trucks in the airport area and the airport access roadways, thus enhancing both the roadway access capacity and safety as well as reducing adverse environmental impacts such as emissions and noise. If the UFT lines are connected to intermodal rail terminals, the reduction in truck traffic in urban highways will extend beyond the airport access roads to the overall urban roadway network which in turn would have wider congestion mitigation and emissions and noise reduction benefits for the overall region.

4.3. Problem statement

DFW airport is one of the busiest airports in the nation (Airports Council International, 2016). The proposed UFT line has the potential to substantially reduce the truck traffic within the DFW Airport grounds and thus improve safety, efficiency, and air quality. In 2014 there was almost an equal amount of imports and exports; about 298,600 metric tons of imports and about 300,000 metric tons of exports (Bureau of Census, 2015). These cargos are currently transported by trucks from the cargo terminals. Assuming each truck is fully-loaded to its maximum legal weight (about 22 metric tons of cargo), there would be about 27,000 fully-loaded trucks per year coming into or leaving the air terminals. The proposed UFT line would alleviate the need for these trucks to enter the secured airport area and instead enter the perimeter UFT terminus point. Such systems would have the potential to reduce the number of trucks on urban roadways, thus enhancing both the roadway capacity and safety as well as reducing adverse environmental impacts such as emissions and noise.

4.4. Identifying Terminal Points

One end of the UFT system should be close to the DFW cargo terminal so loads can be embarked directly from the airplane to the UFT system. The other terminus point for the DFW airport UFT system must be close to the major highways in the area, so trucks can easily reach the terminal to pick up or unload their freight. The terminal also should have compatible land use with the surrounding area, so its 24-hour operation is not disruptive. Based on an examination of the DFW Master Plan, industrial land use has the highest compatibility with a distribution center and terminal activities. Three potential candidate sites with compatible land use are considered for the satellite terminal location. These include the Northwest Logistics Center, the International Commerce Park (northeast of the airport), and the Proposed Intermodal Freight Terminal southeast of the airport. Figure 4.1 highlights the location of all three suggested terminal points in relation to the cargo terminal and surrounding roadways.

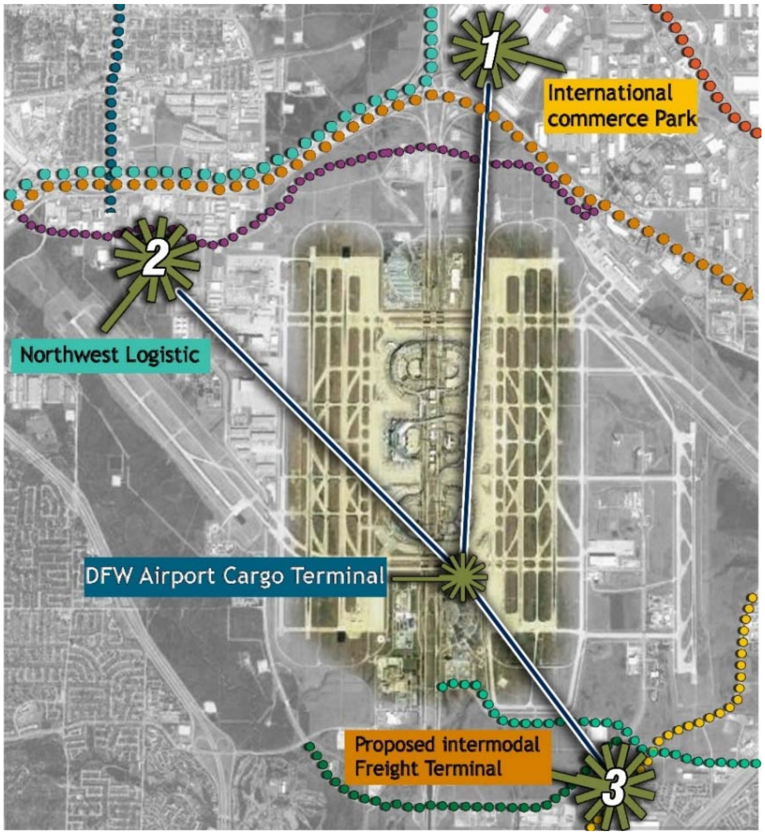


Figure 4.1 Candidate Terminal Sites in relation to Access Roadways

The access highways to the Northwest Logistic Center and the International Commerce Park are already operating at levels of service C and D. The access roadways for the proposed intermodal Freight Terminal are all at level of service A. The calculation of level of service for each access road is attached in Appendix A. Given the above, the proposed intermodal freight terminal appears to be the most suitable candidate for the off-airport satellite terminal for the UFT line.

4.5. Design Characteristics

4.5.1 Cargo Dimensions

In the design of the tunnel and vehicle, the International Air Transport Association (IATA) A-2 Crate is considered as the design freight size, namely the IATA Type A-2 (Code: DAA) crate. As illustrated in Figure 4.2, this crate is 125 inches long, 88 inches wide, and 79 inches high (317 cm×223 cm× 200cm). It has a maximum gross weight of 13,300 lbs or 6 metric tons.

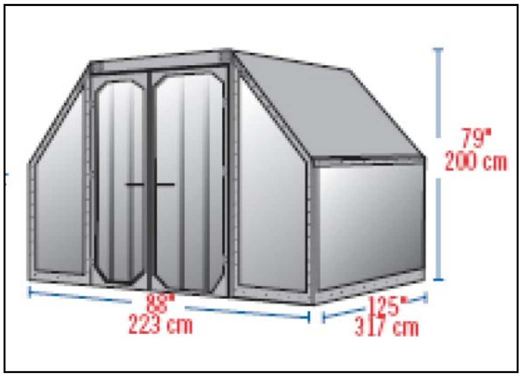


Figure 4.2 Air Crate Shape and Dimensions

4.5.2 Tunnel Construction

A straight tunnel can be used to connect the two proposed terminus points. As illustrated schematically in Figure 4.3, the distance between the two points is 8,100 ft. For the aforementioned freight size, a cylindrical tunnel is envisioned. Cylindrical tunnels are more suitable where Tunnel Boring Machines (TBMs) are to be used, such as in this application where runways and taxiways cannot be disrupted by using cut-and-cover construction methods.

The depth of the tunnel, considering the soil conditions and underground utility lines is considered to be 40 ft. Tunneling using TBM is recommended for this project. This method has the least impact on the normal operation of the Airport. Based on the diameter of the tunnel and geotechnical considerations, the segmental lining is suggested for the tunnel structure and lining.

4.5.3 Vertical Shaft and Ventilation

For ventilation and maintenance purposes, a vertical access shaft is also needed at or near the halfway point between the two terminus points. Based on the utility map of the DFW airport, station 35+00 seems to be an appropriate point for the vertical shaft since there is no interference with any runway or taxiway operations and no buried utility lines exist at that location.

Vertical shaft is a main component of a tunnel design in freight pipeline system. It is necessary for reducing the air resistance force and balancing the air pressure on both sides of the vehicle. In a study Lundgren analyzes the merits of vents in the freight pipeline system and points out that “if there were only one tightly fitting capsule in a long tube, with no air vents for relief, the capsule would have to push the entire column of tube air against the frictional resistance of the tube walls” (Lundgren, 2000).

Based on the utility map of DFW International Airport and the proposed route, a 13-ft. diameter access shaft is designed 3,500 ft. from the UFT origin terminal. The access shaft is used for construction logistics and ventilation during tunnel construction and UFT operation. It also facilitates access to utilities and expedites spoil removal. One of the main applications of the vertical shaft is in emergency stop cases, where it provides quick access. In case of vehicle breakdown, backup forklifts are predicted in each terminal. There are also back up vehicles in terminals to substitute for a damaged vehicle. It is recommended to provide a truck access road between two terminals to work as an alternative in case of UFT system breakdown. Figure 4.3 shows the suggested location of vertical shaft.

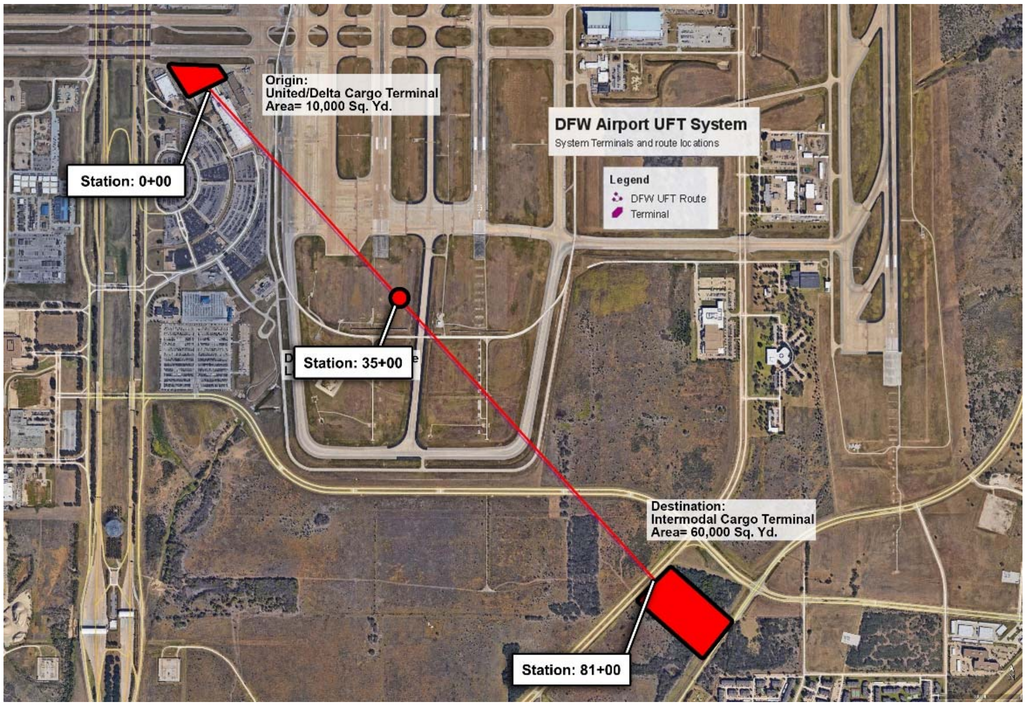


Figure 4.3 Location of Terminals and Vertical Shaft

4.5.4 Running Gear Systems

Three running gear systems are studied to design the most reliable and cost-effective running gear system for the proposed UFT system. The studied systems are Maglev (Magnetic Levitation), rubber tire, and steel wheel and rail systems. These systems are compared based on ride quality, material durability, required maintenance, and capital and operating costs.

Rubber tire systems have high traction that makes them more desirable for sloped routes. They offer smoother ride quality, and they are able to stop or reach the highest design speed in a shorter time in comparison with the regular steel wheel and rail systems. However, they have high energy consumption due to high tire friction and high maintenance requirements (Roop 2000). Although the capital cost of rubber tire systems is less than the other two systems, high maintenance and reliability issues associated with these systems (such as tire blow-outs) render them undesirable for the proposed UFT system.

The steel wheel and rail system is more reliable than the rubber tire system and has lower maintenance costs. Besides, the environmental pollution and energy consumption of steel wheels and rail are lower than the rubber tire system. The problem of braking and sliding of steel wheel and rail will be solved when it is used in combination with an LIM propulsion system (Vollenwyder, 2006). In an LIM system, steel wheels only carry the vehicle weight and the acceleration/deceleration will be generated through the induction force.

Maglev systems are among the most recent running systems used to move trains. These systems levitate vehicles on guideways using electromagnetic force. The absence of wheel in these systems offers higher ride quality, lower maintenance, and higher speeds compared to rubber tire and steel wheel and rail systems (Lee, 2006). Nevertheless, lack of experience and substantial capital cost of Maglev systems makes them unsuitable for the proposed UFT system (Roop 2000).

Comparing all the functional and economic aspects of the studied running gear systems, the steel wheel and rail with LIM propulsion is identified as the most suitable gear system for the proposed DFW UFT system.

4.5.5 Propulsion system

The right propulsion system can make a UFT more environmentally-friendly than other modes of freight transportation. The application of linear electric motors in rail transportation is a rather new concept. For the first time, Japan used Linear Induction Motors (LIM) in combination with steel track and wheels in the Osaka metropolitan subway in 1990. LIM found further applications in people movers, light rails, and subways around the world. This includes the JFK International Airport people mover system, the SkyTrain in Vancouver, the Detroit people mover system, and the Kuala Lumpur LRT System (Kaye, 2004). Transportation systems with magnetic levitation, such as Shinkansen (Japan Bullet Train), HyperLoop and Pipe§net (Cotana, 2008), usually use Linear Synchronous Motors (LSM) as the propulsion systems. LSM has permanent magnets and is more compatible with the MagLev systems (Thornton, 2009).

In the linear motors, windings are embedded in the primary and must be connected to electricity. The secondary consists of a conductive sheet like aluminum or copper on top of iron (Montgomery, 2001). Two different topologies for linear motors can be identified: long primary/short secondary and short primary/long secondary. In the long primary configuration, the active part (primary) will be installed on the guideway between the rail and the passive part (secondary). The secondary, in turn, will be attached to the vehicle. Long primary configuration is costly and is not suitable for long-distance routes (Kaye, 2004). It is possible to provide stationary LIMs in regular distances in long LIM configuration (Turkowski, 2016) but still the cost of installation and maintenance is higher than installing the LIM on one vehicle. Also, this system is not suitable for short vehicles as the distance between the Linear Induction Motor (LIM) plates should be close to the vehicles length in case of emergency stop or breakdown.

Linear induction motors are the perfect propulsion system for UFT applications. Their light weight, low maintenance, small size, powerful braking and precise stopping make the linear motors the appropriate option for a UFT system. The short primary LIM has a simpler and more reliable configuration. The proposed UFT system uses single detached vehicles for transportation of freight. As such, the recommended propulsion system is the short primary LIM which best suits the requirements and specifications of the proposed UFT system. The air drag force must be considered in the LIM design and calculation of energy required for operation of the UFT system. Different parameters affect the air resistance against movement of the vehicle including the shape of the vehicle, air density, and vehicle size. The air resistance force increases with the vehicle speed.

4.5.6 Vehicle Design

The designed vehicle is rectangular, and its minimum dimensions for accommodating an IATA A-2 crate are 7.8 W× 7.5 H× 14.3 L. Covered vehicles are not recommended for the airport UFT system as there is little chance of load spillage in closed crates. Also, crates themselves can be climate-controlled if needed. Therefore, an open flat-bed vehicle design with a rectangular cross-section is recommended for crates. Extra space in the tunnel is required for utilities, walkways, maintenance and aerodynamics of moving vehicles. Containers are placed or retrieved from the side. Figures 4.4 and 4.5

show the cross-section and longitudinal sections of the designed airport UFT system, respectively.

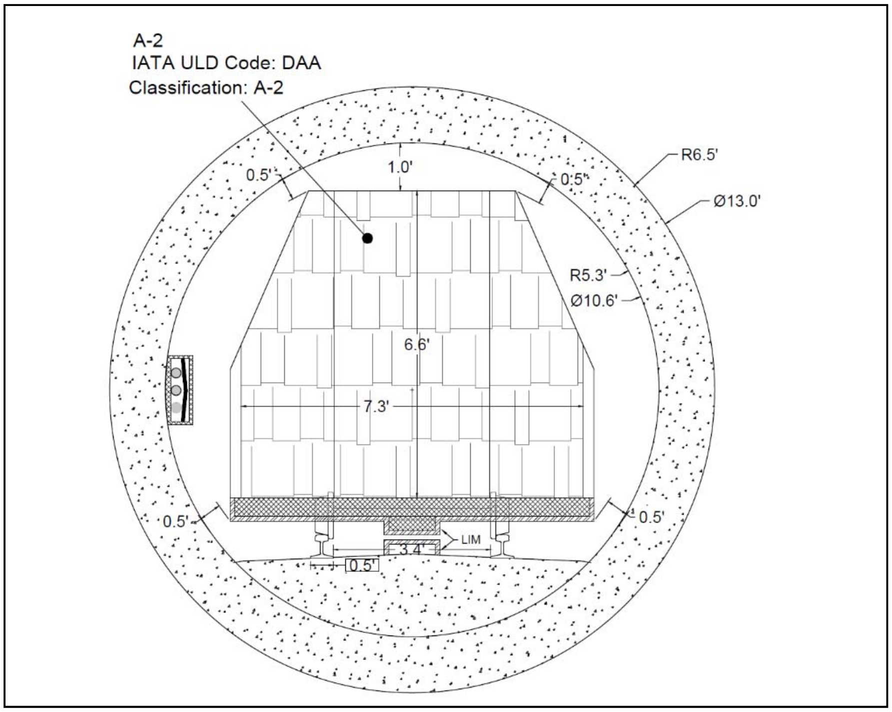


Figure 4.4 Cross Section of the Designed UFT System

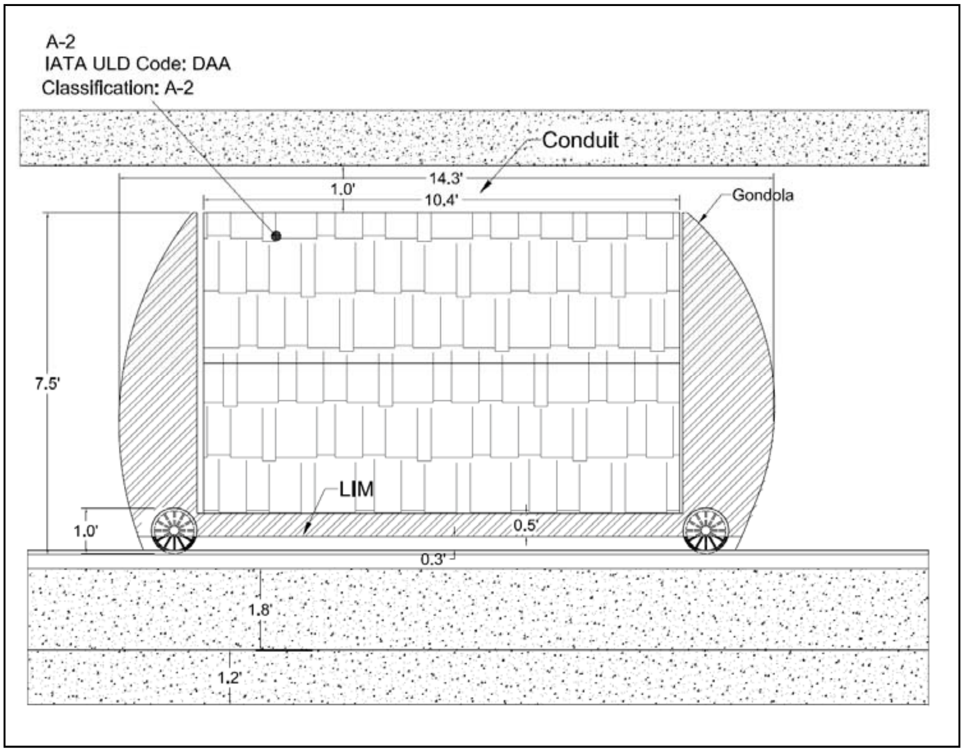


Figure 4.5 Longitudinal Section of the Designed UFT System

4.5.7 Entry/Exit Ramp

Two general approaches are available for designing the freight pipeline entry/exit systems: sloped ramps and vertical shafts (Liu, 2006). The vertical shaft system is very energy intensive and requires the design of electric lifts for transporting the crates to the surface. The slope ramp system is a more environmentally-friendly solution that uses the gravitational force for accelerating the vehicle in the entry ramp and decelerating it in the exit ramp. The goal in this section is to find the optimum slop e for the entry /exit ramp of the UFT system.

In a LIM system, the induction force between primary and secondary provides the propulsion force for moving the vehicle. Contrary to the conventional rail system, the friction between steel wheels and rail is not used for the acceleration or braking of the vehicle. In this system wheels only hold the load weight and provide low friction movement. Because of this non-contact propulsion feature, UFT and generally all transportation systems with LIM are able to ascend or descend steep grades. Using a steep grade is more applicable in a UFT system since moving in steep grades in passenger systems may be uncomfortable. A steep entry/exit ramp for UFT saves energy at the entry ramp for acceleration of the vehicle and also saves energy in deceleration at the exit ramp. It also decreases the land requirement by shortening the at-grade length of the railway.

The limiting parameter in designing the entry/exit slope is the possibility of sliding the vehicle on the ramp when it is stopped, and the LIM system is off. The force that prevents the vehicle from sliding on the ramp is the static friction between the steel wheels and the rail. The static friction coefficient between the steel wheels and rail to be μ_s=0.3 in wet conditions and μ_s=0.5 in dry condition (Kapoor, 2000). As represented schematically in figure 4.6, forces acting on the vehicle are:

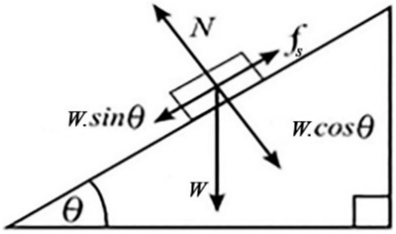


Figure 4.6 Affecting forces on UFT Vehicle in Entry Ramp

$F_s = \mu_s \cdot W \cdot \cos\theta$ (Eq. 1)

and

$F_w = W \cdot \sin\theta$ (Eq. 2)

Where F_s is the static friction force between the rail and steel wheel and F_w is the weight component that pulls down the vehicle. In these equations, W is the weight of the vehicle in lbs and θ is the exit/entry ramp inclination with respect to the plane in degrees. According to the diagram, as long as $(\mathrm{F}_s \geq F_w)$, the vehicle does not slide on the rail. Solving the equation for θ will result in $(\tan\theta \leq \mu_{s)}$. Therefore, the grade of the entry/exit ramp should be less than the static friction coefficient between the steel wheel and rail. Hence, the entry/exit ramp grade in UFT system should be less than 30%.

Although the slope for UFT system can be up to 30% but maintenance and installation of equipment is more difficult on a higher slope. Considering a safety factor for the ramp grade, the proposed slope for the UFT entry/exit ramp is suggested to be around 20% or 12 degrees.

4.6. Terminal Design

Figure 4.7 shows the schematic design of the proposed UFT terminal for the DFW airport. The proposed design has two similar sections, one for unloading the vehicle and the other for loading the crates onto the vehicle. The total area of the terminal without access roads is estimated to be 21,700 sq. ft. It has one loading/unloading platform and two layover/maintenance rails at the end of the rail line. The stacking area would require an 8-inch thick concrete pavement and would have a storage capacity of 70 crates.

As presented schematically in Figure 4.7, the access road to the terminal has two lanes: a truck (driving) lane and an access lane. The rail line cuts the terminal in half. The terminal will have two gates. At one gate trucks are unloaded by forklifts, and at the other gate, trucks are loaded, also by forklifts. Four forklifts will be handling the loading/unloading operations in the terminal area. In addition, one backup forklift is kept at each terminal side to replace any forklift which may have to be taken offline for recharging or maintenance.

All freight should be checked before loading to the plane. The screening systems can be placed either in the “Intermodal Freight Terminal” before loading to the UFT system or in the “Airport Cargo Terminal” before loading to the airplane based on the airport policy. Providing the inspection system in the intermodal terminal increase the safety and security of the UFT system.

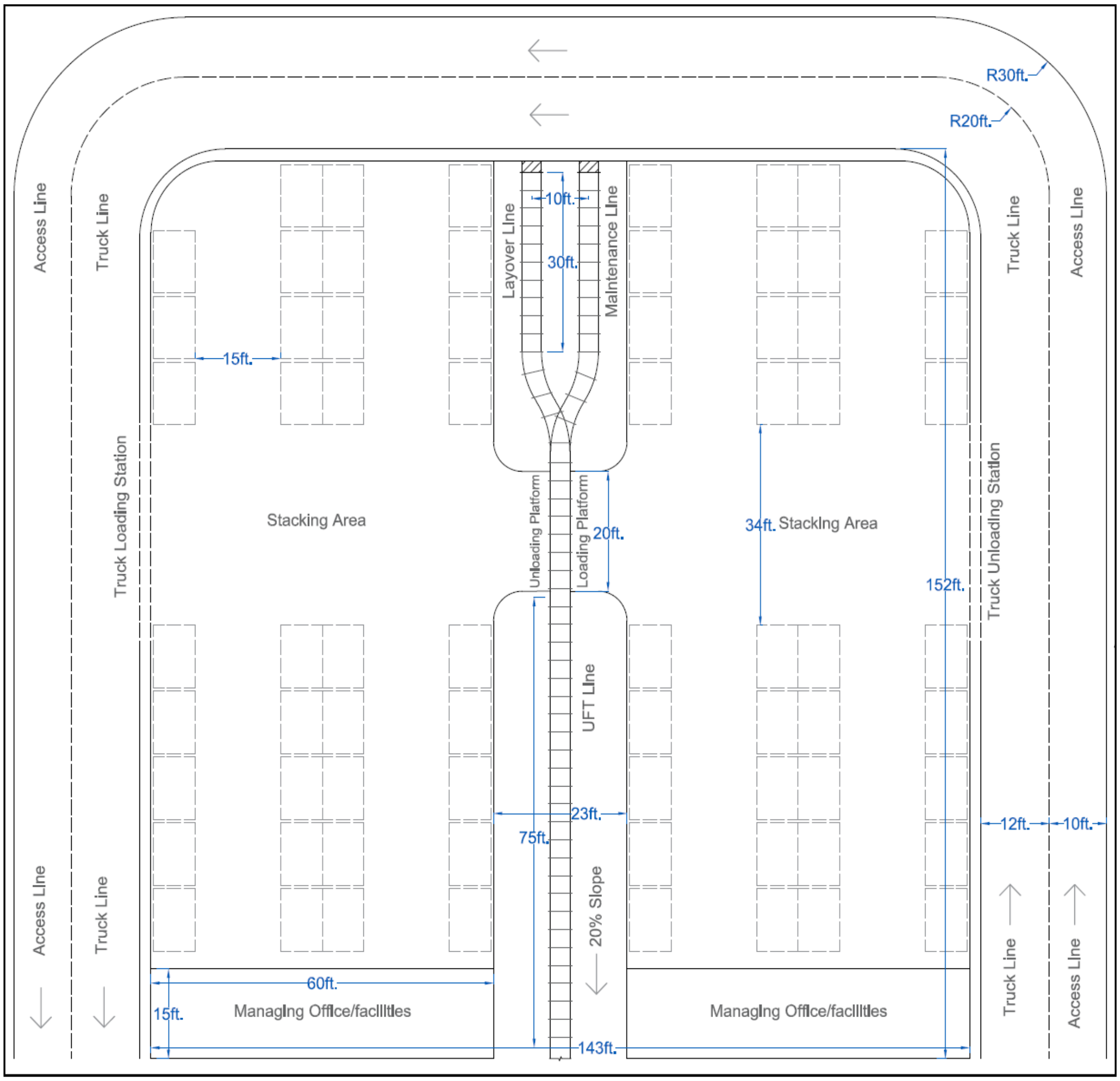


Figure 4.7 Schematic Design of Terminal

4.7. Operational Analysis

4.7.1 Headway

In the UFT system operational analysis, the prevailing parameter in determining capacity and speed of the system is headway. In a single-track UFT system like the DFW airport UFT system, headway is a function of the round-trip travel time and the required loading/unloading time in terminals. At each terminal, forklifts would need about one minute to unload an arriving vehicle and load a departing vehicle. Forklift operators need five minutes to stack the unloaded crates in the stacking yard or, on the other side of the terminal, to carry a crate from the stacking yard to a departing vehicle. The analysis of required times by forklifts in the terminal, will result in minimum system headway of six minutes.

4.7.2 Speed

In the six-minute headway time, the vehicle has one stop at each terminal and should travel the distance between terminals twice. The dwelling time required in each terminal is one minute. Therefore, the return trip for the vehicle should take four minutes, i.e., a two-minute one-way travel time. The travel time between two terminals in UFT system can be calculated as in equation 4.1. (Najafi, 2016):

$$t = \frac{L}{1.47\,v} + 0.735v\,\left(\frac{1}{a} + \frac{1}{d}\right) \qquad \text{Eq. 4.1}$$

Where:

t= One-way travel time between two terminals (secs);

L= One-way route length (ft);

v = Running speed (mph);

a= Acceleration rate (ft/sec^2);

d= Deceleration rate (ft/sec^2).

Due to the use of LIM system in the UFT system, the acceleration/deceleration rates can be considered equal (a=d) and happen along the entry/exit ramps, respectively. The ramp length for the proposed UFT system, with 40 ft. depth and 20% slope, is 204 ft. The acceleration/deceleration rate to get to the speed *v* follows equation 4.2:

$$a = \frac{v^2}{2l} \qquad \text{Eq. 4.2}$$

Where:

l= Entry/exit ramp length (ft.);

v = Running speed (mph);

a= Acceleration rate (ft./sec^2).

Considering (a)=(d) and replacing (a) from equation 4.2 in equation 4.1 yields equation 4.3 below for calculating the running speed for the UFT system.

$$v = \frac{1}{t}\left(\frac{L}{1.47} + 2.94\, l\right) \qquad \text{Eq. 4.3}$$

Where:

L= One-way route length (ft.);

l= Entry/exit ramp length (ft.);

t= One-way travel time between two terminals (secs);

v = Running speed (mph).

Based on the specifications of the UFT system design, the distance between the two terminus points is 8100 ft. and the ramp length is 204 ft. With the two-minute one-way travel time, the speed of the UFT vehicle comes out to be about 51 mph. This speed seems to be a reasonable speed for freight movement, and it is comparable with other modes of freight movement (Truck and Rail). Generally, freight needs a low cost, energy efficient and reliable movement rather than an expensive, fast and fancy movement.

4.7.3 Capacity

The capacity of the UFT system in each direction in a day can then be calculated as in equation 4.4. (Najafi, 2016):

$$C = 3600\frac{T}{h} \quad \text{Eq. 4.4}$$

Where:

h= Design headway (sec);

T= Working hours in a day (hr/day);

C = System capacity (veh/direction/day).

If we consider the DFW airport UFT system to operate 24 hours a day, with a headway of six minutes, the capacity of the system will be 240 vehicles per direction per day. Considering the six-metric ton capacity of each crate, the UFT system can transport 525,600 metric tons annually in each direction. The capacity of the designed UFT system is higher than the current demand in the DFW airport and can accommodate the future growth in air cargo transportation.

4.7.4 Terminal Operation

The operation of forklifts is the main component in the operation of the UFT terminal. Four forklifts are needed for terminal operation, two for loading/unloading the UFT vehicle and two for loading/unloading the trucks. Each UFT vehicle stays in the terminal for one minute. In this one-minute time, the vehicle should be unloaded and loaded. Each forklift has five minutes to take the crate to the staking area. The stacking area has a storage capacity of 70 crates. There is one stand by forklift in each terminal in case of any lift breakdown or scheduled maintenance.

4.8. Conclusion

The proposed short-haul UFT system transports standard air crates between an airport cargo terminal and a distribution center off the secured airport area. The DFW Airport case study has included design configurations of the track, vehicles, propulsion system, end-point terminals, and loading/unloading mechanisms at those terminals. Operational attributes such as speed, headway, loading/unloading time, and line capacities are also determined.

The proposed UFT line has the potential to substantially reduce the truck traffic within the DFW Airport and thus improve safety, efficiency, and air quality. The DFW Airport handles some 600,000 metric tons of cargo annually, with almost a 50/50 split between imports and exports. These shipments are currently transported by trucks from the airport cargo terminals; this translates to about 27,000 fully-loaded trucks per year coming into or leaving the air terminals. The proposed UFT line would obviate the need for these trucks to enter the secured airport area.

Based on an analysis of cargo volumes, availability of space, and access roadway capacity, the location of the two terminus points of the UFT line are determined. The proposed intermodal freight terminal in the southeast corner of the airport grounds is deemed to be the most suitable candidate for the off-airport terminus point, with cargo terminal being the on-airport terminus point. A straight tunnel is used to connect the two proposed terminus points. The distance between the two points is 8,100 ft.

In the design of the tunnel and vehicle, the International Air Transport Association (IATA) A-2 Crate is considered as the design freight size. For this frieght size, a cylindrical tunnel is proposed. A tunnel depth of 40 ft is selected. This depth is selected based on both the soil conditions and to avoid underground installations such as buried utility lines. For the vehicle, an open flat-bed design with a rectangular cross-section is recommended. The flat-bed configuration is recommended since the A-2 crate is a covered crate itself. Furthermore, the time to load or unload the crates at the terminals is minimized with a flat-bed vehicle. The vehicles are steel-wheeled and operate because they are more reliable than the rubber tire systems and have lower maintenance costs (Roop 2001). Besides, the environmental pollution and energy consumption of steel wheels and rail are lower than those of a rubber tire system (Barkan, 2007).

In terms of terminal configuration, the proposed terminal design is to have two similar sections, one for unloading and the other for loading the crates onto the UFT vehicles. It has one loading/unloading platform and two layover/maintenance rails at the end of the rail line. At each terminal, four forklifts will be handling the loading/unloading operations. The backup forklifts are needed to replace any active forklift which may have to be taken offline for recharging or maintenance.

To minimize the construction and operating costs, a single-track rail system is proposed. In this system, a single vehicle will traverse the track between the two terminals. In this manner, the headway of the system will be a function of the travel time between the terminals as well as the loading/unloading time in terminals. At each terminal, forklifts would need about one minute to unload an arriving vehicle and one minute to load a departing vehicle. The round-trip travel time between terminals is about four minutes. This, along with the two minutes needed by forklifts to load or unload the vehicle, will result in minimum system headway of six minutes. Note that the four-minute round-trip travel time is estimated based on the 8100 ft. distance between the two terminus points and an operating speed of about 50 mph. If the UFT system operates 24 hours a day with a headway of six minutes, the capacity of the system will be 240 vehicles (crates) per direction per day or 525,600 metric tons annually. The capacity of the UFT system is higher than the existing annual demand of 300,000 metric tons per direction in DFW Airport and as such can accommodate the future growth in air cargo transportation. It is noteworthy that designing a longer vehicle that can accommodate two crates or coupling two vehicles together can almost double the capacity of the system with the current speed or lower the required speed and energy while maintaining the designated capacity.

Chapter 5. Propulsion System Design and Energy Analysis for Underground Freight Transportation Systems

5.1.Introduction

The demand for freight transportation is on the rise as a result of population growth, increase in the need for energy, and the expansion of global trade. Existing infrastructure for freight transportation seems inadequate for future growth, and new facilities are required to cover the deficiencies in cargo movement. Underground Freight Transportation (UFT) is a new mode of transportation that uses the space below the ground to carry cargo within individual vehicles in tunnels and pipelines. Different propulsion systems have been used for freight pipeline systems. The goal of this research is to find the proper propulsion system for the UFT system. In addition, this research aims at finding the minimum power of the propulsion system and energy consumption for the UFT system operation. Two short-haul and long-haul UFT systems with different load sizes are used to test and apply the results of this research. The findings of this research suggest that because of its light weight and short thickness, a Linear Induction Motor (LIM) is the most appropriate propulsion system for UFT Besides, this research estimates that the energy consumption and power requirement of a LIM system is low. The energy consumption of LIM system is calculated as a function of UFT system operating speed. Therefore, the results of this research can be applied in the design, operation and cost estimating of other UFT systems (Shahooei, 2018).

5.2. Research Objective

An Underground Freight Transportation (UFT) system can play a significant role in making up some of the future capacity shortfall in the over-ground freight transportation.

UFT offer multiple benefits, including: decreasing truck traffic on highways, reducing energy consumption, reducing noise and air pollution, promoting safety and security, and enhancing the reliability of freight delivery. A UFT system is an automated transportation system that carries freight in individual capsules or flat-bed gondolas.

The goal of this chapter is to identify the best propulsion system and estimate the required energy power of the propulsion system. This paper also intends to be a reference for operation of a UFT system so the calculated energy and power is established as a function of UFT vehicles running speed. The results from this research can be applied to UFT or other freight pipeline systems.

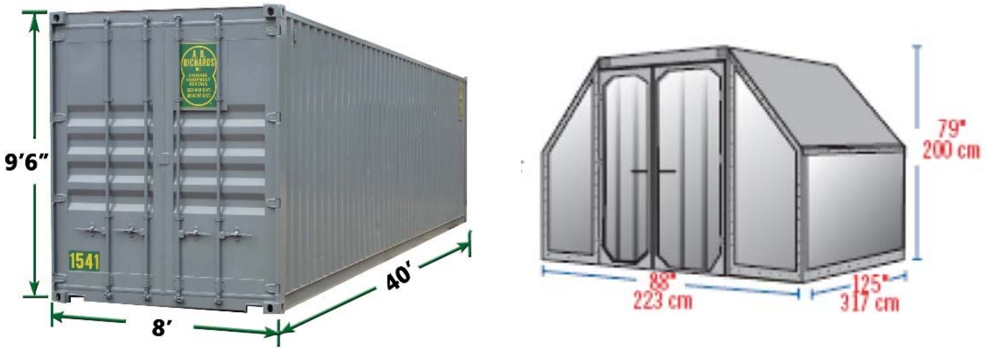
5.3. UFT System Design

5.3.1 Route

This research considers two routes. A short-haul route located in Dallas-Fort Worth (DFW) International airport and connects a cargo terminal to a proposed intermodal freight terminal southeast of the airport; this route has a total length of 8,100 feet. The long-haul route connects the Port of Houston to a proposed intermodal inland port south of Dallas and is 250 mile long. In both intermodal terminals, trucks can unload or pick up a load.

5.3.2 Load

With technical advances in the design of linear induction motors as well as tunnel boring machines, UFT systems may carry different load sizes. The study considers two different loads for the UFT system. A shipping container is 40 ft long, 8 ft wide, and 9.5 ft high, can accommodate 20 US pallets and a maximum gross weight of 68,000 lbs. An International Air Transport Association (IATA) A-2 crate is 10.4 ft long, 7.3 ft wide, and 6.6 ft high, and can have up to 13,300 lbs. in gross weight. The shipping container size UFT system is most suitable for transportation of cargo from and to sea ports. The air crate load is considered for transferring loads on the short-haul route from cargo terminals to warehouses. Figure 5.1 shows the shape and size of each load type.



(a) Standard Shipping Container (b) IATA A-2 Crate

Figure 5.1 Shape and Size of (a) Shipping Container and (b) Air Crate

5.3.3 Vehicle

The vehicles for freight transportation may be covered capsules or flatbed gondolas. The capsules are typically metallic with a hatch door at one end of the capsule for placement or retrieval of cargo. Covered capsules are recommended for pallet size loads to prevent load spillage. Covered capsules are not recommended for the shipping containers or air crates because load spillage in closed containers remains unlikely (Najafi, 2017). Therefore, an open flat-bed gondola with a rectangular cross-section can be considered for shipping containers and air crate transportation.

5.3.4 Tunnel

The tunnel is the underground space required for freight transportation. The tunnels are mostly made by concrete pipes but in smaller sizes, steel pipes may also be used. For this application, the tunnels can be as deep as 40’-60’ depending on soil conditions and other underground installations such as buried utility lines. Figures 5.2 and 5.3 show the schematic design of the shipping container and air crate UFT systems.

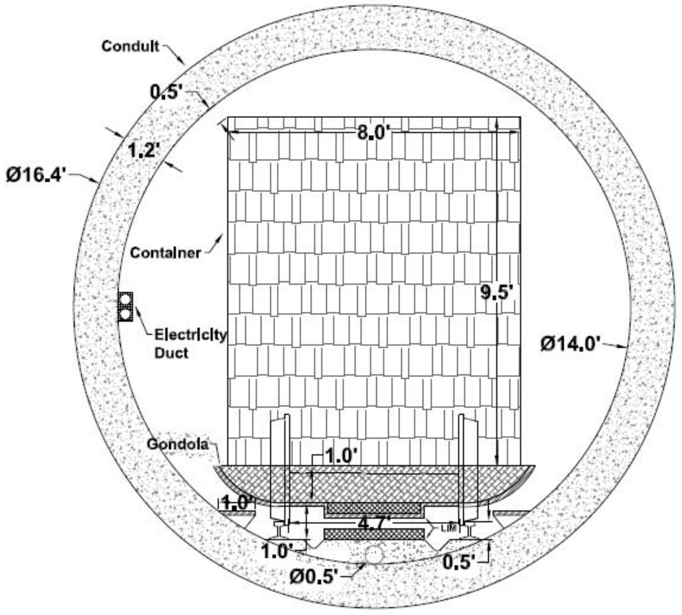


Figure 5.2 Schematic Design of the Standard Shipping Container UFT System

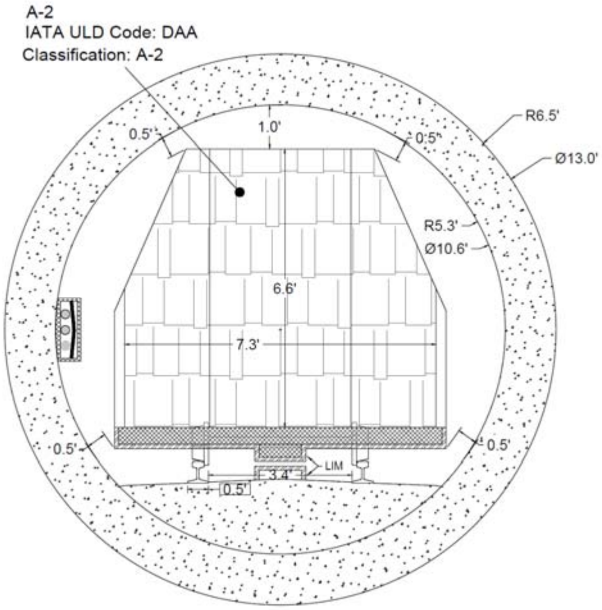


Figure 5.3 Schematic Design of the IATA A-2 Air Crate UFT System

5.4. Propulsion System Configuration

An environmentally-friendly UFT system requires a propulsion system that has the lowest pollution but also delivers enough force for propulsion of the vehicles. Generally, two different propulsion systems are used in underground freight pipelines, pressure-propelled pneumatic systems or electrical motors. Pneumatic Capsule Pipelines (PCP) have serious limitations with respect to the size and length of UFT systems (Roop, 2000). The right propulsion system can make a UFT more environmentally-friendly than other modes of freight transportation.

The application of linear electric motors in rail transportation is a rather new concept. For the first time, Japan used Linear Induction Motors (LIM) in combination with steel track and wheels in the Osaka metropolitan subway in 1990. LIM found further applications in people movers, light rails, and subways around the world. This includes: the

JFK International Airport people mover system, the SkyTrain in Vancouver, the Detroit people mover system, and Kuala Lumpur LRT System. (Kaye, 2004)

5.4.1 Rotary vs. Linear Motor

Electric motors suitable for UFT systems can be divided into two categories: linear motors and rotary motors. Rotary electric motors have been in use for a long time in tramway and metro systems. In these systems, a rotary motor is installed on the vehicle and propels the vehicle along the rail way through the friction between the steel wheel and steel track. This type of motor is usually bulky and heavy, which increases the vehicle size and weight and in turn affects energy consumption and tunnel size in underground systems (Woronowicz, 2014). Rotary motors also need more maintenance compared to linear motors. In addition, rotary motors cannot provide a stopping force; therefore, a separate system for braking is required in vehicles with a rotary motor propulsion system (Vollenwyder, 2006).

A linear electric motor is a general term for a non-adhesive propulsion system which generates linear movement through induction or magnetic thrust. In a rotary induction motor two different parts provide the motion: stator and rotor. The stator is the constant part around the motor and consists of several windings. The rotor is the moving part that rotates around an axle. When the stator is connected to an electrical current, the resulting induction force makes the rotor rotate. (Hellinger, 2009). Assume flattening a rotary motor, in which case the stator becomes the active part and is called “primary” and the rotor becomes the passive part and is called “secondary”. In this case, however, the rotor (secondary) instead of rotating moves along the stator (primary) (Hellinger, 2009). Figure 5.4 shows the relation between rotary and linear electric motors.

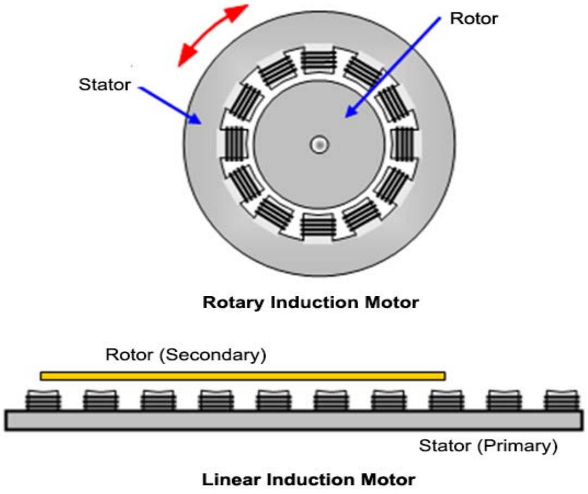


Figure 5.4 Comparing rotary and linear induction motors

5.4.2 Short Primary vs. Long Primary

In a linear motor the location of the primary and secondary is interchangeable. In linear motors, windings are embedded in the primary and must be connected to electricity. The secondary consists of a conductive sheet like aluminum or copper on top of iron, and unlike the primary, it does not need to be connected to an electricity source (Montgomery, 2001). Two different topologies for linear motors can be identified: long primary/short secondary and short primary/long secondary.

In the long primary configuration, the active part (primary) will be installed on the guideway between the rail and the passive part (secondary). The secondary, in turn, will be attached to the vehicle. Long primary configuration is costly and is not suitable for long distance routes. Also, this system is not suitable for short vehicles as the distance between the (Linear Induction Motor (LIM) plates should be less than the vehicle length. (Kaye, 2004)

In the short primary configuration, the primary will be installed on the vehicle and the secondary will be placed between the rails. (Kera, 1999) This configuration increases the vehicle weight and is not suitable for high speed transportation systems. However, its cost is lower than the long primary configuration. In the short primary configuration, the vehicle should be connected to an electricity source at all times. Schematic design of the short primary configuration is presented in figure 5.5.

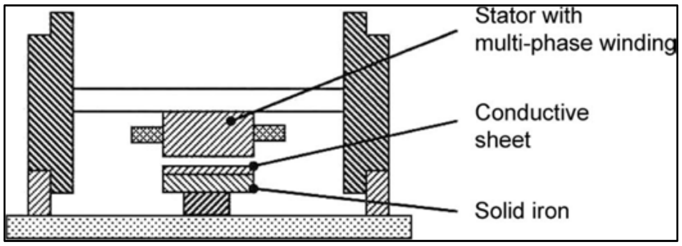


Figure 5.5 Short primary/long secondary configuration of LIM on a vehicle

5.4.3 LIM vs. LSM

The Linear Synchronous Motor (LSM) system uses windings with three-phase Alternating Current (AC) electricity for generating the induction thrust that moves the passive plate. In LSM, permanent magnets will be installed on the vehicle and a changing electric magnet will be placed on the guideway. Then, the electric current should be synchronized with the location of the vehicle and the permanent magnets to create the magnetic field that pushes the vehicle forward. The efficiency of a LSM is higher than LIM but its installation cost is also higher. Besides, the operation of a LSM is more complex and requires more maintenance. (Kaye, 2004).

The main challenge in the design of a LIM system is maintaining the gap between the primary and the secondary. This gap should be between 10 and 12 mm; otherwise, the efficiency of the system will decrease significantly. The suspension system of the vehicles should be designed in a way that even with a maximum load no contact happens between the plates. Meanwhile, in an empty vehicle, the gap should not exceed the aforementioned distance. In practice, prior experience with LIM-based passenger transportation systems indicates an optimum gap is achievable (Isobe, 1999). Gap control is easier for freight transportation systems than passenger systems because the suspension system may be less comfortable and the vehicle can be more rigid.

In the design of long primary LIM systems, the distance between LIM plates should be less than the vehicle length so that enough LIM plate is available beneath the vehicle to push the vehicle in case of an emergency stop. Moreover, a malfunction in the LIM system with long primary configuration will shut down the entire system. In the case of an LIM breakdown in the short primary configuration, the vehicle can be taken out or substituted with a backup vehicle (Thornton, 2009).

The LIM system uses windings with three-phase AC electricity for generating the induction thrust that moves the passive plate. In LSM, permanent magnets will be installed on the vehicle and a changing electric magnet will be placed on the guideway. Then the electric current should be synchronized with the location of the vehicle and the permanent magnets to create the magnetic field and to push the vehicle forward. The efficiency of LSM is higher than LIM but its installation cost is also higher. Besides, the operation of LSM is more complex and requires more maintenance. For example, synchronization of the location of the vehicle should be controlled constantly, otherwise it could result in malfunctioning of the system. Because of the cost and complexity of the LSM system, the short primary configuration of this system is not practical (Kaye, 2004). Figure 5.6 Shows the LSM system configuration.

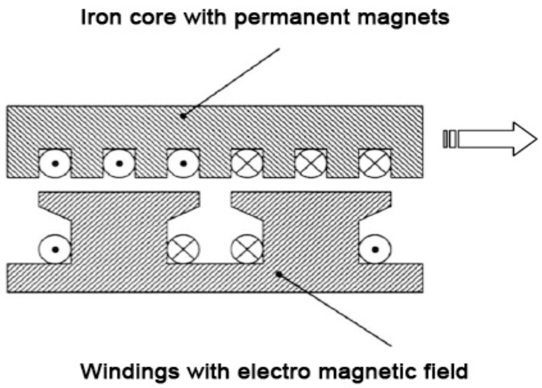


Figure 5.6 Long Primary LSM Configuration

5.5. Energy and Power Requirement

Different parameters affect the energy consumption of a UFT system. The friction between the rail and steel wheels, air drag force, cruising speed, acceleration/deceleration rate and entry/exit ramp slope are identified as the main elements affecting energy consumption. The objective of this section is finding the effect of each element on energy consumption and formulating each element in order to calculate the energy consumption for a UFT system.

5.5.1 Entry/Exit Ramp Slope

In a LIM system, the induction force between primary and secondary provides the propulsion force for moving the vehicle. Contrary to the conventional rail system, the friction between steel wheels and rail is not used for the acceleration or braking of the vehicle. In this system wheels only hold the load weight and provide low friction movement. Because of this non-contact propulsion feature, UFT and generally all transportation systems with LIM are able to ascend or descend steep grades. Using a steep grade is more applicable in a UFT system since moving in steep grades in passenger systems may be uncomfortable. A steep entry/exit ramp for UFT saves energy at the entry ramp for acceleration of the vehicle and also saves energy in deceleration on the exit ramp. It also decreases the land requirement and destruction by shortening the at grade length of the railway.

The limiting parameter in designing the entry/exit slope is the possibility of sliding the vehicle on the ramp when it is stopped and the LIM system is off. The force that prevents the vehicle sliding on the ramp is the static friction between the steel wheels and the rail. If we consider the static friction coefficient between the steel wheels and rail to be μ_s=0.3 in wet condition and μ_s=0.5 in dry condition (Kapoor, 2000). According to figure 5.7, affecting forces are:

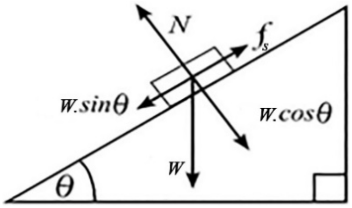


Figure 5.7 Affecting forces on UFT Vehicle in Entry Ramp

(Eq. 1)

and

$F_s = \mu_s \cdot W \cdot \cos\theta$ Eq. 5.1

and

$F_w = W \cdot \sin\theta$ Eq. 5.2

Where F_s is the static friction force between the rail and steel wheel and F_w is the component of the weight that pulls down the vehicle. In these equations W is the mass of the vehicle in lbs. and θ is the exit/entry ramp inclination with horizontal plane in degrees.

According to the diagram, as long as $(\mathrm{F}_s \geq F_w)$, the vehicle does not slide on the rail. Solving the equation for the parameter θ will result in $(\tan\theta \leq \mu_{s)}$. Therefore, the grade of the entry/exit ramp should be less than the static friction coefficient between the steel wheel and rail. Hence, the entry/exit ramp grade in UFT system should be less than 30%.

Although the slope for a UFT system can be up to 30% but maintenance and installation of equipment is harder on a higher slope. Considering a safety factor for the ramp grade, the proposed slope for the UFT entry/exit ramp of the UFT system is suggested to be around 20% or 11.3 degrees.

5.5.2 Gear System Resistance

The rolling resistance is an important parameter that should be considered in the energy requirement calculation for UFT system. The rolling resistance between the rail and steel wheel is a function of the vehicle weight and is formulated as follows:

$$F_r = C_r \cdot W \cdot \cos\theta \qquad \text{Eq. 5.3}$$

In this equation, *W* is the weight of fully loaded vehicle in lbs. and *Ɵ* is the exit/entry ramp inclination with horizontal plane in degrees. The slope for the entry/exit ramp in UFT terminal is designed to be 20% or 11.3 degrees. C_r is the rolling resistance coefficient for steel wheel and rail which is considered to be 0.001 (2017). Maximum friction force happens when the vehicle carries the maximum allowable load. The total vehicle weight and friction force for the shipping container and air crate systems are calculated in table 5.1.

Table 5.1 Friction Force for each UFT System

UFT System	**Total Vehicle Weight (lbs.)**	**F_r: Friction force (lbf.)**
Shipping Container	92,000	92
Air Crate	20,800	21

5.5.3 Air Drag Force

The air drag force must be considered in the calculation of energy required for operation of a UFT system. Different parameters affect the air resistance against movement of the vehicle including shape of the vehicle, air density, and vehicle size. The air resistance force increases with the vehicle speed. In fact, the air resistance is proportional to the square of the object speed. Equation 5.4 is used for calculating the air resistance force for a moving object:

$$F_d = C_d . \rho \frac{AV^2}{2g} \qquad \text{Eq. 5.4}$$

In this formula, ρ is the air density which is considered to average 0.075 lb. per ft^3 in DFW area and g is gravitational acceleration (32.17 ft/s^s). C_d is a coefficient of air drag which depends on the shape of the vehicle. The typical air drag coefficients for different objects are shown in table 5.2 (Elert, 2017):

Table 5.2 Typical Air Drag Coefficient for Different Objects

Object or Shape	**C_d**
ideal rectangular box	2.1
skydiver	1.0~1.4
person standing	1.0~1.3
bicycle	0.9
ideal sphere	0.5

tractor-trailer, heavy truck	0.7~0.9
tractor-trailer with faring	0.6~0.7
suv, light truck	0.35~0.45
typical car	0.25~0.35

Designed UFT vehicles are similar to the trailers. Therefore, the air drag coefficient is considered to be 0.7. *A* is the object surface area facing the moving direction. The air resistance force for each system can be defined as a function of speed. If we consider the speed of the shipping container UFT system as 45 mph (66.15 feet/second) and the speed of the crate system 51 mph (74.97 feet/second), then the air drag force can be calculated for each system. Table 5.3 shows the calculation of air drag force for each UFT system. The relation between the speed of each system and the air drag force is illustrated in figure 5.8.

Table 5.3 Air Drag Force for each UFT System

UFT System	**Area (ft^2)**	**F_d (V)**	**Speed (ft/sec)**	**F_d: Air drag force (lbf.)**
Shipping Container	88	$0.072 \times V^2$	66.15	315
Air Crate	52	$0.042 \times V^2$	74.97	236

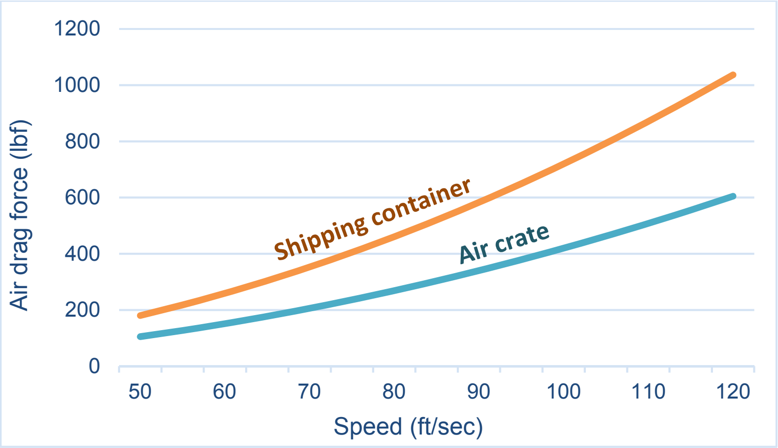


Figure 5.8 Relation Between Speed and The Air Drag Force in each UFT system

5.5.4 Speed at the End of the Entry Ramp

The gravity force in the entry ramp accelerates the vehicle, which allows one to calculate the vehicle speed at the end of the entry ramp. This helps to find the energy required to obtain the desired speed in the tunnel. On the entry ramp, the gravity force pulls the vehicle and friction and the air drag forces resist the movement. Based on the law of conservation of energy, the difference between the potential energy at the beginning of the ramp and kinetic energy at the end of the ramp equals the work done by air drag and friction forces. Formula 5.5 shows the mathematical expression:

$$Wh - \frac{mv^2}{2g} = d(f_d + f_r) \qquad \text{Eq. 5.5}$$

In this equation, h is the depth of the tunnel and d is the length of the ramp. The d value for a ramp with depth of 40 and 20% slope equals to 204 ft. F_r is constant and equals to values in table 1 for each load system. F_d is not constant and is proportional to the speed of the vehicle. Due to the quadratic relation of F_d to V, the average of F_d for each system can be calculated through integration of air drag force function of V as in equations 5.6 and 5.7:

Shipping Container: $f_d = \frac{1}{v - v_0}\int_{v_0}^{v} 0.072 V^2 .dv = 0.024 v^2$ Eq. 5.6

Air Crate: $f_d = \frac{1}{v - v_0}\int_{v_0}^{v} 0.042 V^2 .dv = 0.014 v^2$ Eq. 5.7

Solving the equation 6 and 7 for both the shipping container and air crate system has the same result. We can conclude that, although the effects of friction and air drag are different on each system, the speed of the vehicle in both the shipping container and the crate system at the end of the ramp is 34.3 mph or 50.5 ft/sec.

5.5.5 Acceleration Force

For vehicles to get to the desired velocity, the LIM system should provide an acceleration force. The previous calculation shows that vehicle obtains a speed of 50.5 ft/sec without any additional force from the LIM. If V is assumed to be the desired cruising speed of the vehicle at the end of the ramp, the acceleration rate required along the ramp imposed by the LIM system, can be calculated through equation 5.8:

$a = \frac{V^2 - 50.5^2}{408}$ Eq. 5.8

Based on this equation, the required acceleration rate for the UFT system to get to the suggested speed of 45 mph is 4.5 ft/sec^2. Using Newton's second law (*F=ma*), the force required by the LIM system to get each vehicle to the desired speed is presented in Table 5.4:

Table 5.4 Required Force for Acceleration of Vehicle

UFT System	**Speed (ft/sec)**	**F_a(V)**	**F_a (lbf.)**
Shipping Container	66.15	$7.01(V^2 - 50.5^2)$	12,797
Air Crate	74.97	$1.58(V^2 - 50.5^2)$	4,851

5.5.6 LIM System Power

In order to transport the vehicle in the tunnel with the desired speed, the LIM system should overcome the rolling resistance and air drag forces. The LIM should also provide enough force to accelerate the vehicle to the desired speed. Equation 5.9 shows the required force that should be provided by LIM.

$$F_{LIM} > F_r + F_d + F_a \qquad \text{Eq. 5.9}$$

The power of a propulsion system is the result of the force exerted by the LIM times the average speed of the vehicle resulting from that force (Equation 5.10). Based on each force, the required power of the LIM system can be calculated as a function of speed. Equations 5.11 and 5.12 shows the LIM system power accordingly for shipping container and air crate UFT system as a function of vehicle cruising speed. Table 5.5 shows forces that LIM should overcome and its required power. Figure 5.9 illustrates the relation between LIM power and the running speed of UFT vehicle.

$$P_{LIM} = F_{LIM} \times v \qquad \text{Eq. 5.10}$$

Table 5.5 Affecting Forces on Moving Vehicle and Required LIM Power

	Speed	**LIM Required Forces**			**Required Power**	
UFT System	(ft/s)	F_r (lbf.)	F_d	F_a (lbf.)	ft.lbf./sec	K.Watt
Shipping Container	66.15	92	$0.024V^2$	$7.01(V^2 - 50.5^2)$	427,735	580
Air Crate	74.97	21	$0.014V^2$	$1.58(V^2 - 50.5^2)$	184,793	250

$$P_{Container} = 3.51V^3 - 8893V \qquad \text{Eq. 5.11}$$

$$P_{Crate} = 0.8V^3 - 2004V \qquad \text{Eq. 5.12}$$

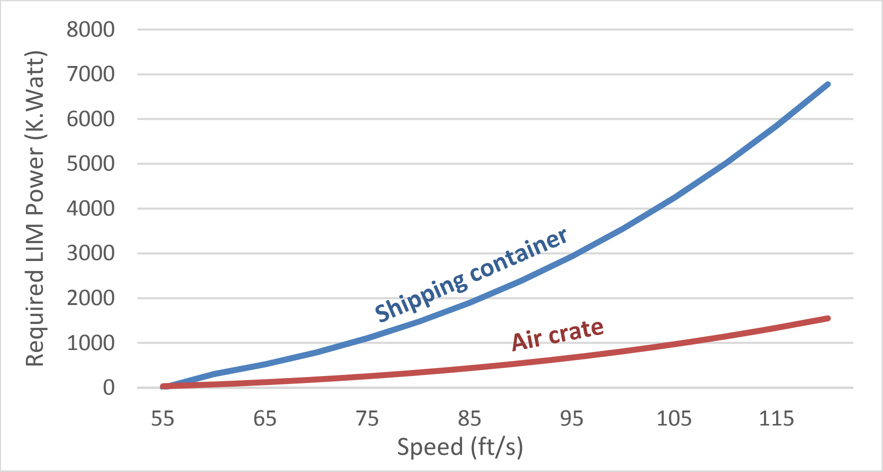


Figure 5.9 Required LIM power According to the Speed of Vehicle

5.5.7 System Energy Consumption

In physics, energy consumption (work) is calculated by the force times the distance the force is imposed. The total work done by the LIM is the summation of the friction force, air drag force, and acceleration force times their respective distances. Equation 5.13 shows the calculation for the total energy required for transportation of one load in UFT system:

$$E_{LIM} = F_r \times l + F_d \times l + F_a \times d \qquad \text{Eq. 5.13}$$

Where:

F_r: Resistance force

F_d: Air drag force

F_a: acceleration force

d= Entry/Exit ramp length

l= UFT route length

By substituting parametric formulas for each variable, the total energy can be calculated as a function of speed (Table 5.6):

Table 5.6 Forces and respective distances for operation of a UFT system

	Friction		**Air drag**		**Acceleration**	
UFT System	Force	Length (ft)	Force	Length (ft)	Force	Length (ft)
Shipping Container	92	1,320,000	$0.072 \cdot V^2$	1,320,000	$7.01(V^2 - 50.5^2)$	408
Air Crate	21	8,100	$0.042 \cdot V^2$	8,100	$1.58(V^2 - 50.5^2)$	408

Equations 5.14 and 5.15 express the total energy required for one-time transportation of one load from a terminal to the other terminal as a function of speed.

$$E_{Container} = 97900\mathrm{V}^2 + 121261223 \qquad \text{Eq. 5.14}$$

$$E_{Crate} = 985\mathrm{V}^2 - 870402 \qquad \text{Eq. 5.15}$$

The total energy consumption for transportation of one load in a shipping container and crate system in feet pound of force, can be expressed as in table 5.7. Figure 5.10 also shows the change in energy consumption in relation to the cruising speed of the UFT vehicle.

Table 5.7 Required Energy for Movement of one Vehicle in UFT System

	Speed	**Required Energy**	
UFT System	(ft/sec)	ft.lbf.	KWH
Shipping Container	66.15	549,654,245	207.0
Air Crate	74.97	4,665,791	1.8

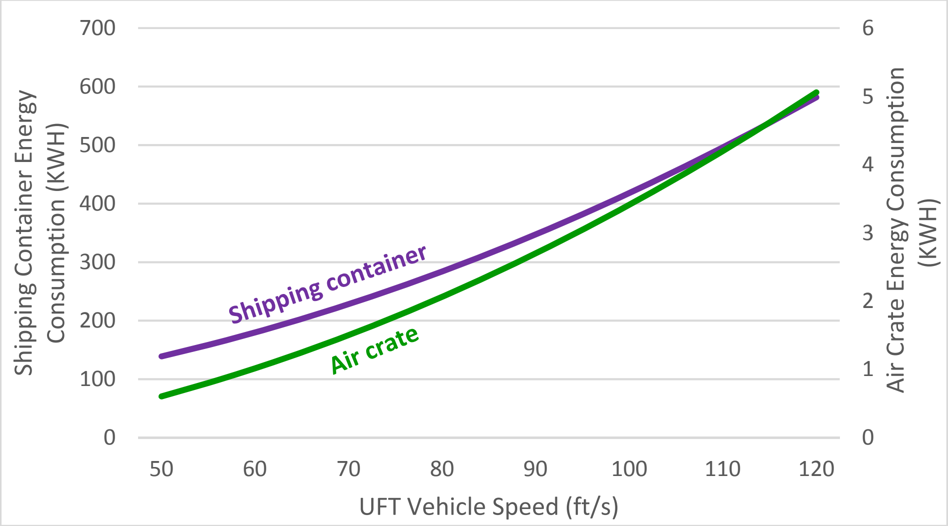


Figure 5.10 Energy Consumption of Each UFT system according to speed

5.6. Conclusions

Linear electric motors are a perfect propulsion system for UFT applications. Their light weight, low maintenance, small size, powerful braking and precise stopping make the linear motors the appropriate option for a UFT system. The short primary LIM has a simpler and more reliable configuration compared to a LSM and its cost is lower. The permanent magnets in the LSM system and the necessity of location and current synchronization, makes the LSM an unreliable propulsion system for UFT (Kaye, 2004). The proposed UFT system uses single detached vehicles for transportation of freight. Hence, in the long primary configuration, the distance between the LIM plates should be less than the vehicle length, which makes it costly and less reliable. As such, the recommended propulsion system, is the short primary LIM which best suits the requirements and specifications of the proposed UFT system. Table 5.8 summarizes the advantages and disadvantages of each linear propulsion system.

Table 5.8 Advantages/Disadvantages of LIM/LSM systems

Linear Motor System	**Configuration**	**Advantages**	**Disadvantages**
Linear Induction Motor (LIM)	Short Primary	Lower construction cost Similar to conventional rail No-contact Acceleration No-contact Braking All weather function Precise stopping location Simple track switch Easy maintenance Steep grade capability	Sensitive to gap Low energy efficiency Heavier vehicle Vehicle connect to electricity
	Long Primary	No-contact Acceleration No-contact Braking All weather function Precise stopping location Steep grade capability	Low energy efficiency Sensitive to gap Expensive for long haul High maintenance
Linear Synchronous Motor (LSM)	Short Primary	Technically not recommended	Complicated Expensive Impractical
	Long Primary	Higher efficiency No-contact Acceleration Steep grade capability No-contact Braking All weather function Precise stopping location	Complex operation Needs synchronization

The study of energy and power requirements of a LIM system identifies several forces on the UFT vehicle while it is in operation. The rolling resistance force is a function of total vehicle weight and exists throughout the UFT route. The air drag force is a function of UFT vehicle speed and is greater in higher speeds. As a result of gravitational force, in a 40 ft deep tunnel, the UFT vehicle reaches the speed of 34.3 mph at the end of the entry ramp. This speed is a function of the tunnel depth and is independent from vehicle weight or size. Results from the study of forces on UFT vehicle show that the shipping container system needs 207 KWH and air crate system requires 1.7 KWH energy for the transport of one load in one direction. The calculations show that the minimum power of a LIM system for the shipping container is 117 horsepower and for air crate is 44 horsepower.

Chapter 6. Summary and Conclusion

Texas with three major ports, two international airports, and a long border, with Mexico, is a major hub for cargo entering the United States. The demand for freight is increasing, and the existing infrastructure appears insufficient for transporting the future freight demand because the nation's main transportation infrastructure, including highways and railroads already operate at or near capacity in many locations. Without a solution, highways will become more congested and railways will face unbearable challenges. Predictions suggest that although trucking is and will remain the major mode of freight transportation, new technologies will result in emerging innovative and intermodal freight transportation systems. These new modes of freight mobility will accommodate the excess freight transportation demand and will provide new alternatives for freight distribution and delivery. Underground freight transportation systems represent one of the new mobility systems that have gained popularity in recent years, and multiple studies and projects are ongoing in different countries. The application of underground space for transportation is not something new, but the objective, scale, configuration, and size of the new freight pipeline systems make them different from previous underground transportation systems. The invention of both Linear Induction Motors (LIMs) and Tunnel Boring Machines (TBMs) make larger size UFT systems with longer routes possible. The freight pipeline systems produce less pollution than other modes of freight transportation. UFT is a closed system dedicated to freight transportation, so it is safer and more secure.

The purpose of this research is to investigate the feasibility of employing a variety of underground freight mobility technologies that allow for the optimized use of the available highway capacity. Freight pipeline transportation is a class of autonomous transportation systems where close-fitting capsules or flat-bed vehicles carry freight through tunnels between intermodal terminals. Using a part of the underground space of the existing right-of-way of highways, specially interstate highways, may facilitate the construction of such tubes and reduce their construction costs. Linear induction motors (LIM) and automation technologies provide effective means of propulsion for transporting full-size shipping containers as well as smaller crates and pallets. By considering planning, design, and operation methods, this research examines the use of underground freight pipelines in three proposed routes in Texas as described in previous chapters.

To gain a better understanding of the system components and design alternatives, literature on previous freight pipelines either proposed as a concept or constructed as a demonstration project were investigated. This review included studies conducted for the Federal Highway Administration (FHWA) by Volpe and others (Vance, 1994), the Sydney Freight Circle for container transport from the Port of Sydney to seven distribution warehouses (Fiars, 2009), the container port expansion project in Shanghai (Guo, 2008), and currently operating systems in the mining industry (Liu, 2005) (Kosugi, 1999). In addition, proposed systems such as a Port Authority of New York and New Jersey UFT line proposed by Liu et al. (Liu, 2004) and the Freight Shuttle System proposed by Roop et al. (Roop, 2000) were examined. These reviews, along with inputs from projects like Mole in UK, Cargocap in Germany, Pipe&Net in Italy, and Cargo Sous Terrain in switzerland formed the basis for the schematic design of various elements of the UFT system, including the capsule and tunnel design, the track and gear system, the propulsion and power system requirement, and the terminal design as well as planning potential short-haul and long-haul starter lines. Most research and studies in freight pipeline systems concentrate on the economic feasibility and construction method. However, this research focuses on developing design standards for UFT systems and formulating required equations for corresponding to the system operation.

Moreover, the operational attributes of freight pipeline systems from a transportation engineering perspective is analyzed and formulated. The optimum speed of the system is determined, and based on cruising speed, the minimum headway is calculated. The system capacity is calculated based on minimum headway. The relation between the headway and system flow is also identified. The study formulates the required loading/unloading time in the operation of the intermodal terminal, based on the number of vehicles in use, number of loading/unloading platforms, and number of lifts/handlers. The design of the terminal provides multiple platforms and bypass shunts to allow for all vehicles to unload/load in the required time.

Three different routes are defined in this dissertation for the application of freight pipeline systems. The first route is a long-haul route with a length of 250 miles that connects the Port of Houston to Dallas. This route is mainly located below IH-45 and is designed to alleviate the truck traffic along the highway and accommodate the increasing freight transportation demand between Houston and Dallas. The second route is a medium- haul route with a length of 15 miles between the Port of Houston and a distribution center outside downtown Houston. This UFT system aims for the reduction of truck traffic in Houston and its port area, while enhancing the air quality in the region. The third route is designed for DFW airport and is a short-haul route with a length of almost 1.5 miles. This route connects the Cargo Terminal to a suggested freight terminal outside the airport protected zone. Truck traffic in the airport is a major source of concern due to safety, security threats, and air and noise pollution. The DFW Airport UFT system operates environmentally-friendly and can accommodate the current need and future increases in cargo mobility in the airport area.

Different components should be considered for the design of the UFT system. The load size and weight will affect the LIM system, energy consumption, and tunnel size.

Loads can be in a secure container (such as shipping containers or air crates) that can be used with a flatbed vehicle, or they may need a closed capsule to prevent the load spillage (pallets). The tunnel can have a rectangular cross section in rural areas where the cut and cover method is used instead of tunneling. In urban areas where the minimum on-level destruction is required, TBMs can be used for boring round tunnels. Different gear systems can be designed for UFT systems. Because of its higher price and technology, MagLev technologies seems to be unnecessary. Rubber tires need more maintenance and produce more pollution than other gear systems. The best gear system for a UFT is a steel rail and track which has a lower friction and pollution and needs less maintenance. The propulsion system for a UFT can be either pneumatic or electric. Pneumatic systems use air blowers on one side and vacuums on the other side of the capsule to provide enough force to move it. This system is more suitable for short routes with smaller size capsules. Electric motors can be traditional rotary motors or newer Linear Induction Motors (LIMs). The latter is more appropriate for UFT systems because of its lighter weight, smaller size and non-contact operation.

In order to analyze the operation of a UFT system, the relation among vehicle speed, freight capacity, system headway, and terminal configuration should be determined. UFT systems can be either single-track or dual-track. Single track systems can be used in shorter distances or in a network of UFTs with loops. Dual-track systems are most similar to highways with the traffic of vehicles on both directions. Two limiting attributes in the operation of a dual-track UFT system are the minimum safe distance between vehicles and operation of lift/handlers in terminal. Since the suggested UFT system uses individual autonomous vehicles, the required distance for stop in case of emergency is short. This required distance can be expressed in terms of time that comprise the minimum headway of the UFT system. The capacity of the UFT system is when it is working with minimum headway. The speed of the system should be comparable with other modes of freight transportation to keep the system operation efficient and its costs low. The UFT systems, as proposed in this research, are designed to move the cargo in large sizes as an intermodal system, to distribution centers, not end user. So, the freight transportation needs to be reliable, safe, and economic rather than being fast.

Because the speed of lifts and handlers in the terminal is usually lower than the headway of the UFT system, multiple loading/unloading platforms are necessary for the operation of the terminal. The terminal should also provide access roads for trucks, so they can come and pick up their loads. The terminal should be large enough to provide enough space for stacked loads, laid off and back up vehicles and also official space. The configuration of the terminal should guarantee smooth operation and circulation of load in tracks. The operation and configuration of a single-track UFT system is simpler than dual-track systems. The limiting parameters in operation of a single-track UFT are the operation of lifts in the terminal and the transfer time between two terminals, because there is no other vehicle on the rail to define a safe distance. The headway of the system in this case will be the total of the vehicle stop time in each terminal for loading/unloading and the time required for travel between two terminals. Capacity of the system can be calculated by the headway.

Undoubtedly, freight pipeline systems will play an important role in the future of freight transportation because of their advantages in environmental preservation and safety and security in transportation. Most UFT systems designed so far are intermodal systems that receive the freight from a system and deliver it to another location to be distributed by another system (mostly trucks). The future challenge of freight pipeline systems is to design a system that can deliver the load to end-users and work as a network for mobility of cargo in urban areas. The end user may be a supermarket, a restaurant, a company or even a residence. The freight pipeline network requires planning, design, and optimization of the network so that lower length of a UFT network can serve more users. The challenge of automation of such a system can be a research topic for industrial engineers or computer science professionals.

Appendix A: Level Of Service Analysis of Access Roads Around DFW Airport

Location	**Roadway**	**Facility Type**	**Average Daily Traffic (vehs/day/Dir)**	**K-Factor**	**Peak Hour Volume (vehs/hr/Dir)**	**# of Lanes per direction**	**Truck proportion (P_t)**	**Heavy Veh Factor (f_{hv})**	**Peak Hour Factor (PHF)**	**Equivalent Peak Vol. (PC/ln/hr)**	**Design Speed (mph)**	**Density (pc/mi)**	**Level of Service**
Northwest Logistic	N Airfield drive (EB)	Multilane Highway	8,523	0.12	1023	2	0.1	0.91	0.80	639	50	12.8	B
	MAIN St: 5,130 (NB)	Multilane Highway	5,130	0.12	616	2	0.1	0.91	0.80	385	50	7.7	A
	STATE HWY 121 (WB)	Freeway	56,182	0.12	6742	5	0.1	0.91	0.80	1,685	70	24.1	C
International Commerce Park	STATE HWY 114 (NB)	Freeway	49,108	0.12	5893	4	0.1	0.91	0.80	1,842	70	26.3	C
	STATE HWY121 (NB)	Freeway	82,418	0.12	9890	5	0.1	0.91	0.80	2,473	70	35.3	D
	I-635 (EB)	Freeway	62,530	0.12	7504	4	0.1	0.91	0.80	2,345	70	33.5	D
Proposed International Freight Terminal	S AIRFIELD Dr (NB)	Multilane Highway	4,728	0.12	567	2	0.1	0.91	0.80	355	50	7.1	A
	VALLEY VIEW Ln (SB)	Multilane Highway	3,650	0.12	438	2	0.1	0.91	0.80	274	50	5.5	A
	WALNUT HILL Ln (EB)	Multilane Highway	6,559	0.12	787	2	0.1	0.91	0.80	492	50	9.8	A

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