Feasibility of Underground Transport Systems (UTS) for Cargo Distribution within High-Density Urban Landscapes

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Abstract

Evaluation of existing underground transportation systems repurposed for cargo distribution in large cities in conjunction with systems engineering research techniques enabled scope, hypothesis and methodologies to be formed, leading to a cohesive understanding of the possibility of implementation. Further research established a plausible solution to be proposed through utilisation of systems perspective techniques: weighing up risk, cost and sustainability of possible implementation. An automated network that has distribution flows, with a vehicle fleet of approximately 200 powered through Linear Induction Motors (LIM) is the most reliable and cost effective solution at current stages of research. Cost of development is variable depending on size and materials used, but guaranteed increase in costs will be increase diameters of tunnels.

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Introduction

Global urban population is expected to increase to 66% by 2020 (UN 2014), which in turn will place immense stress on current methods of cargo distribution methods within cities. Email and phone correspondence with Peter Carney, Head of Strategy & Development Customised Solutions, of Toll Global Logistics Division confirmed the United Nation's 2014 statistics: as "two-thirds of the world's population will live in six of the largest cities in the world, including: Hong Kong, Singapore, Lagos, and Kuala Lumpur."

Carney's emphasis on the importance of efficiently moving cargo through high density urban landscapes, directed the scope of this investigation towards testing feasibility of underground cargo distribution systems rather than improving road transport modelling software.

Methodology

This investigations philosophical perspective is an objective, consumer-oriented evaluation supported through holistic methods of qualitative and quantitative data (Kumar 2011). Utilisation of an array of system perspective techniques to evaluate the relevance to the client and the city setting.

This investigation seeks to test the feasibility of a city wide underground cargo distribution system design selected through quantitative evaluation of costs, power efficiency, material impact and queuing theory measures. In conjunction with qualitative measures of safety and risk, social and cultural and control theory.

Hypothesis

Developing a hypothesis enables differentiation between two categories that may otherwise be similar and help define a question to be tested against peer-reviewed literature in the field. For this investigation efficiency in mass cargo distribution is a key measurement to the plausibility of an underground network proposed. Commuting rates are an underestimate of the amount of cargo that is capable to be transported using metros and trucks. Metros will be synonymous of underground cargo distribution networks, while buses will represent trucks capability to carry equally as much cargo.

The null hypothesis states there are no significant differences with the rates in which underground networks move cargo. The associated calculated p-value is less than 0.0001 with a degree of freedom of 1. Therefore, the association between the groups (rows) and the two transport methods (columns) are extremely statistically significant.

	Metro	Buses	Row Total
Underground Networks	30 000	3 000	33 000
Other	30 000	1 500	31 500
Column Total	60 000	4 500	129 000

Table 1: Contingency Table representing rates of persons transported per direction per hour for a 5km distance Source: (Thewes 2012)

Background

Pipeline systems for trading has existed since 1810, initially used compressed air to send information from London Stock Exchange with Central Station. Implementation of underground cargo transportation systems evolved into Mail Rail, London's mail and small package delivery system in 1928 (Egbunike & Potter 2011).

Underground Cargo Transport (UTS) offers a space saving alternative compared to traditional cargo distribution methods, that would otherwise need transportation infrastructure and result in congestion (Luo et al. 2010). It also allows for greater flexibility to work with the height dimension that would otherwise be unavailable in traditional systems, paving the way for automation with the drawback of large expanses of energy to move cargo up and down shafts. Encasement of the system enables greater security of cargo transportation and greater reliability due to weather protection, the restricted vision enhances the requirement to automate the system reducing human interaction and the need for people to be in areas of low visibility (Mousavipour 2013).

	Positives Aspects	**Negative Aspects**
Underground Location	Surface space saving	
	Latitude in network design	
		Height Differences
Encasement	Weather Protection	
	Impenetrable	
	Securely Sealed	
		Restricted Vision

Table 2: Fundamental characteristics of underground infrastructure and the consequences. Source: (Van Binsbergen & Bovy 2000)

Layout of underground systems are crucial to the level of automation, ease of accessibility and integration of the systems into traditional cargo transportation methods (e.g. air, water). Van Binsbergen & Bovy 2000 discuss four levels of underground networks with vehicle flow integrated: Object, Section, Link and Network (Figure 1). Underground objects are cellars, or depots, while sections are short, local, tunnels that go under specific urban areas, or land features such as bodies of water. Links are longer, and are more global accessible to fewer vehicle types. Underground networks are highly automated restricted to tailored vehicles for the system.

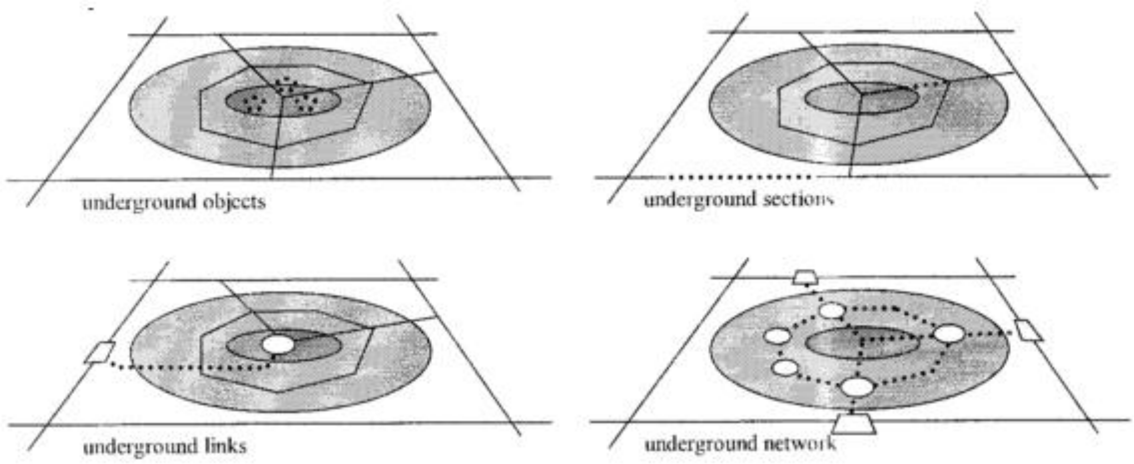


Figure 1: underground network options. Source: (Van Binsbergen & Bovy 2000)

Underground systems efficiency can be determined prior to prototyping through basic flows. Two most basic flows are direct distribution from one origin to one destination (Figure 2 relations), or round trips from origin to multiple destinations (Figure 2 flows). Underground Urban Transprt Systems (UUT) with a flows distribution method yields the shortest average delivery time of 8.4 minutes with the least variance in time of 0.2 minutes (Figure 3). In the setting for a high density urban setting an underground network with a distribution method of round trips is the best option for greatest reliability, mobility and efficiency.

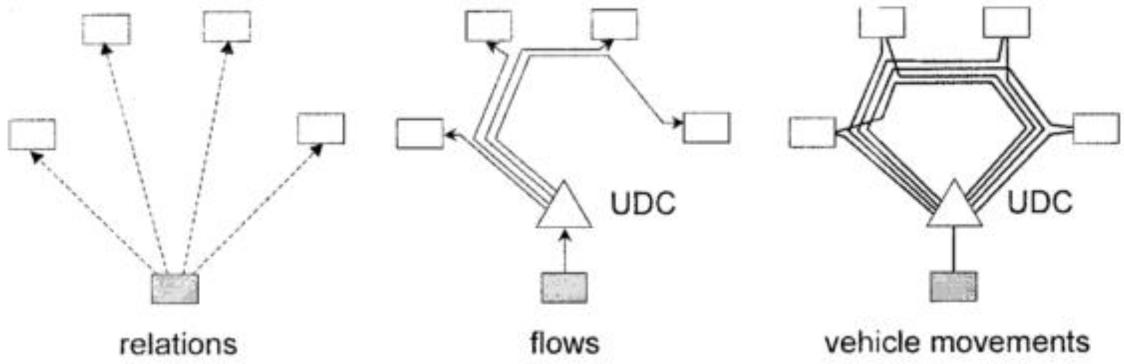
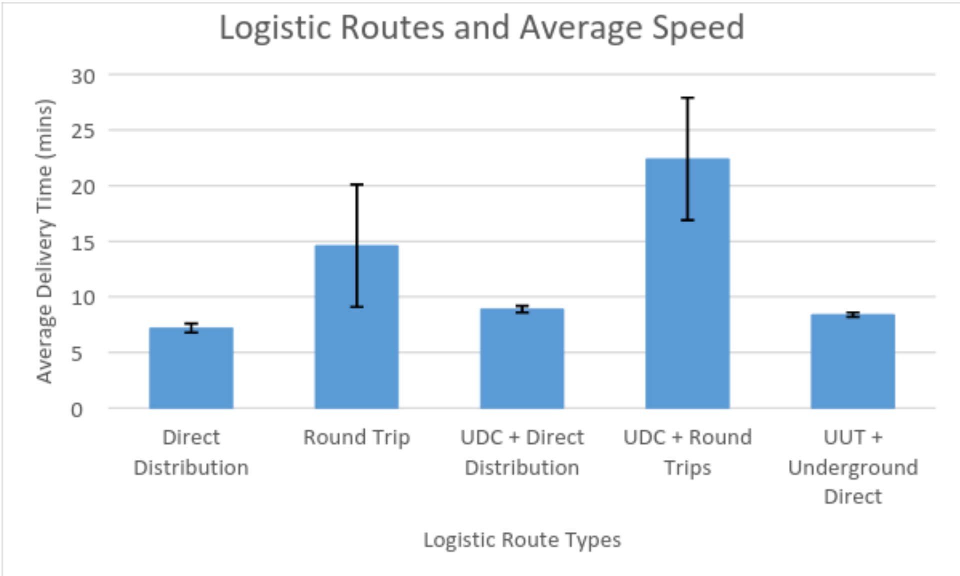


Figure 2: Underground system: direct distribution (model V) urban distribution centre (UDC). Source: (Van Binsbergen & Bovy 2000)



UDC: urban distribution centre or area

UUT: underground urban transport system

Figure 3: Logistic Routes Efficiency through a measure of average speed in minutes. Source: (Van Binsbergen & Bovy 2001)

Existing UTS systems and Cargo Types

Location of underground distribution systems influence the cargo shipments that utilise the provided service and consequently design considerations have to be critically evaluated and incorporated. Mail Rail's system, during its operation period was designed to only carry letters and small parcels through underground tunnels in CBD London, while the new Foodtubes concept is to be a 1500km underground loop that links producers to retailers under the United Kingdom. Italy's Pipe§net network is a high speed, low friction system carrying small volumes of freight in comparison to Amsterdam's Interdepartementale Projectgroep Ondergonds Transport (IPOT) that is much slower in comparison and able to carry larger airport cargo capsules (Egbunike & Potter 2011). Amsterdam's global presence as a flower distributing country allows their UTS system to be tailored to the country's cargo, while it might differ in comparison to Italy's need for a high speed small volume system. In an urban landscape food supply and distribution will continue to grow in demand and as a result London's Foodtubes concept of linking producers and retailers is the most plausible use of a UTS network.

Process perspectives

Efficiency of Propulsion Types

Pielage 2001 discusses proposal vehicles for the IPOT system, refraining it to battery powered systems as traditional combustion engines would result in smog to build up within the enclosed tunnel networks (Table 3). Mousavipour 2013 revisits the idea of using compressed air on larger scales to carry vehicles with cargo weighting up to one ton, but an alternative to such an inefficient system in a city setting is Linear Induction Motors (LIM) (Liu 2004). With current knowledge of LIM powered networks and Liu 2004's comparative analysis of LIM and pneumatic networks in New York City, LIM's are more cost effective and the most energy efficiency system compared to either battery power, or pneumatic networks (Figure 4-6) (Sandalow 2009, Musk 2013).

Vehicle	Wheel Type	Guidance	Steering	Loading	Power
Spykstaal	Rubber Tyre	Electronic	Front wheel	Front and side	DC Electric (battery)
Lodige	Rail + rubber	Electronic	Four wheel	Two side	AC electric Drive (battery + power)
DTM	Rubber Tyre	Self-guided + electronic	Front wheel	One side	AC electric (battery)

Table 3: Specialised vehicles for underground systems (Pielage 2001)

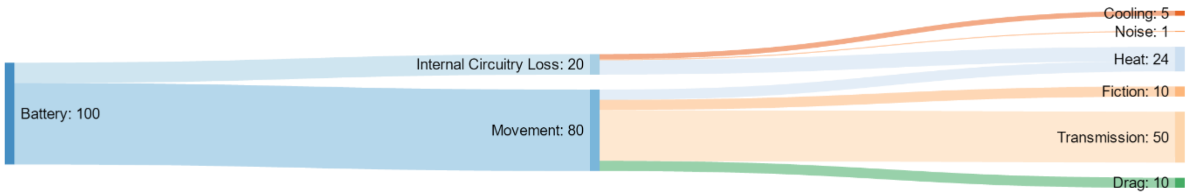


Figure 4: Battery Powered Capsule Energy breakdown. Source: (Sandalow 2009)

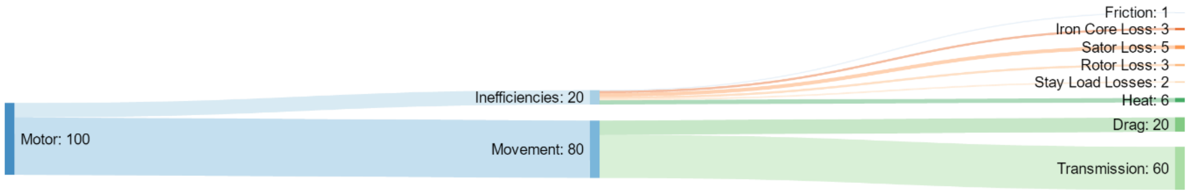


Figure 5: Linear Induction Motor Powered Energy Breakdown. Source: (U.S. Department of Energy: Industrial Technologies Program 2008)

Figure 6: Pneumonic Capsule Pipeline Powered Energy Breakdown. Source: (Musk 2013)

Risk Assessment and Mitigation

Implementation of underground networks as large as a city wide system with incorporation and integration of traditional cargo transportation methods, require detailed risk assessment and mitigation methods thought out prior to approval of construction and running. The two main stages of risk assessment and mitigation are: construction and running stages.

Construction Risk

Rigorous and detailed surveying of the land where construction will occur is mandatory for any system the scale of an underground system. Construction of the tunnel network will cause serious disruptions in high-density urban regions were the cut-and-cover method is just not a viable option. As a substitute to the construction the tunneling boring machine (TBM) can be used at the expense that the cost will be significantly higher. For TBM to be used effectively and the route planned geological stability is a requirement that must be known as it may cause the TBM to become trapped if the walls are highly unstable during dredging. As a result, software analysis is one aspect of methods to gain knowledge on rock profiles and soil types in regions (Mousavipour, 2015). In addition to this information knowledge of city metro systems, utility piping and heritage listed tunnels, catacombs and other structures all may affect viability of cities to implement a UTS.

The possibility of a carbon tax within a country to be implemented may result in increases in costs of running and in turn customer demand of utilization of the system to decrease. Choice of using a carbon neutral electrical power source for the vehicles is a contingency in addition to the previous advantages discussed, while also eliminating carbon sources that can be controlled within the system (Chen & Wang, 2016).

Running Risk

Majority of risks that fall into the risks involved in running an underground distribution system are the integrations with existing transportation methods and cargo distribution industry. Air traffic is a rapidly paced mode of distribution and integration isn't able to be easily programed into the system mainframe to synchronize with plane departure and arrival, but rather refinement over time is required. The best possible alternative is to formulate dynamic system plans for situations that may arise during performance stages (Dunn & Wilkinson, 2015). High risk manufacturers, which translate to guaranteed input and use of the network is difficult to anticipate due to economic variables that are unpredictable. Consequently, minimization of the impact and distribution to multiple input modes is an administrative mitigation strategy when partnerships are initialized (Xue, Choi, & Ma, 2016).

Natural disasters are equally as unpredictable as high risk manufactures, but through substitution alternative traditional transport may be an alternative where UTS have been damaged, otherwise it may continue to run as it's a sealed network from flooding, hail, heavy rain, wind etc (Caunhye, Zhang, Li, & Nie, 2016).

Risk	Risk Type	Likelihood	Impact	Risk Value	Mitigation Strategy	Control Type	Likelihood	Impact	Risk Value after Mitigation	Reference
Air Traffic Networks Reliability	Disruption	Possible	Extreme	High	Dynamic Contingency plans formulated for scenarios that may arise	Administrative	Possible	Moderate	Medium	(Dunn & Wilkinson 2015)
High Risk manufacturer	Operational	Likely	Extreme	Very High	More even distribution among multiple manufacturers	Administrative	Possible	Moderate	Medium	(Xue et al. 2016)
Post natural disaster network reliability	Disaster and Emergency	Possible	Extreme	High	Alternative transportation method (i.e. air, water, land)	Substitution	Possible	Moderate	Medium	(Caunhye et al. 2016)
Customer demand in regards to carbon emission policies reliability	Logistics Services	Likely	Extreme	Very High	Use a carbon neutral power source	Elimination	Unlikely	Minor	Low	(Chen & Wang 2016)
Geological soil stability	Disaster and Emergency	Almost Certain	Extreme	Very High	Software Analysis	Engineering	Unlikely	Major	Medium	(Mousavipour 2015)
Location of building	Disruption	Likely	Major	High	Tunnelling Boring Machine (TBM) method opposed to Cut and cover method	Substitution	Possible	Moderate	Medium	(Mousavipour 2015)

Table 4: Risks and Safety Mitigation of cut and cover and tunnelling excavation methods.

Queue Theory and Feedback Improvements

Air traffic arrival and departure can be highly varied resulting in contingencies for cargo transportation to be implemented, such as storage of cargo in a warehouse prior to the arrival of the plane. This isn't the case for time sensitive cargo such as flowers from Aalsmeer flower auction in Amsterdam's IPOT system (Figure 7). To ensure departure of planes prior to cargo arrival is minimal, dynamic queue systems have been simulated for the Amsterdam Airport Schiphol UTS system.

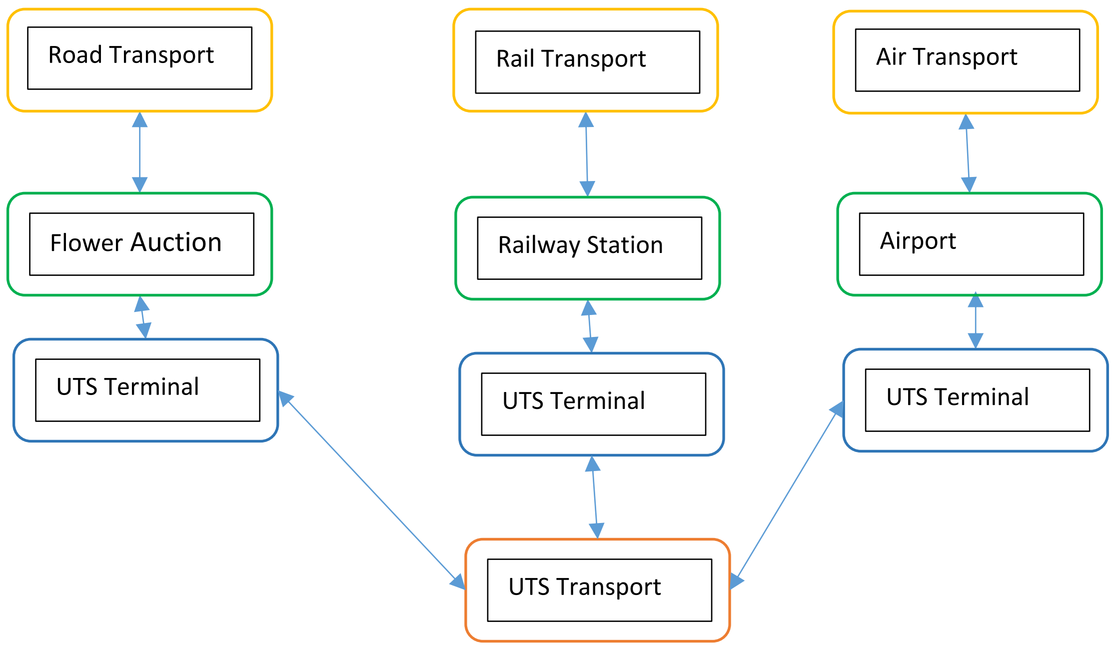


Figure 7: IPOT network breakdown (Van Binsbergen & Bovy 2000)

Queue description of the case study of Amsterdam International Airport Schiphol is a multi-channel queue system, defined by the Flower Auction, Airport, and Railway Station terminals. The cargo is defined as finite arrival rates into an infinitely long list that is inputted into a multi-phase queue system. The queue is then processed through finite queues capped at two cargo shipments per capsule and local to the origin terminal (Figure 8).

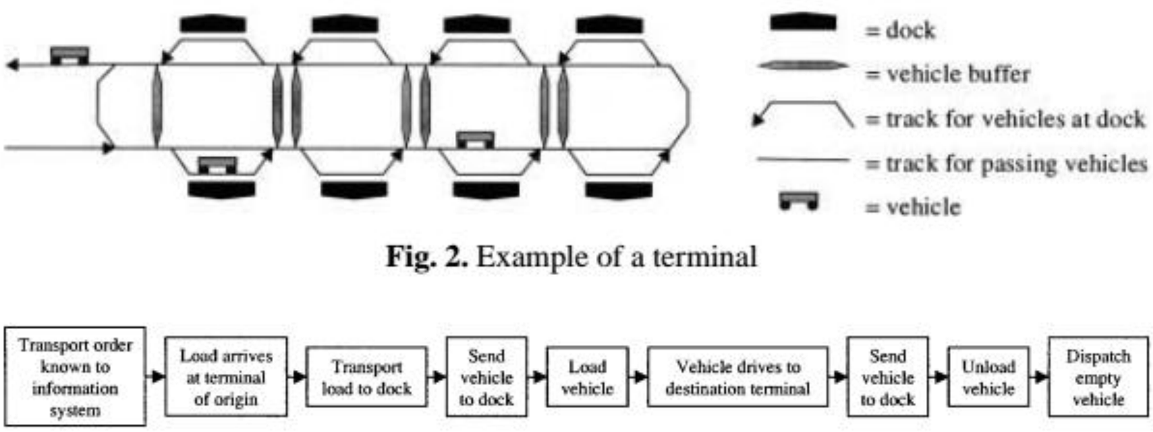


Figure 8: Queue network flow of IPOT system (Van Der Heijden et al. 2005)

Heijden et al. 2001 discusses optimisation methods of empty vehicles to increase fill rate resulting in three major recommendations: 2 docks for each Airport terminal, 5 docks for each Flower terminal and 10 docks for each Railway terminal to meet peak demand throughout a standard business week; an average of 167 active automated vehicles to satisfy fluctuating weekly demand; and an average fill rate of 97.5 when shipments are known 30 mins beforehand and 97.3 for 60 minutes.

A combination of cargo shipments can drastically increase fill rates within the system, but are organised through complex algorithms that rely on the similar arrival times, origin and destination terminals, priority of shipment and minimum delay to other shipments. These recommendations are unique and tailored to the Schiphol Airport's UTS network, but are regardless it is highly insightful for similar systems in the future (Figure 9).

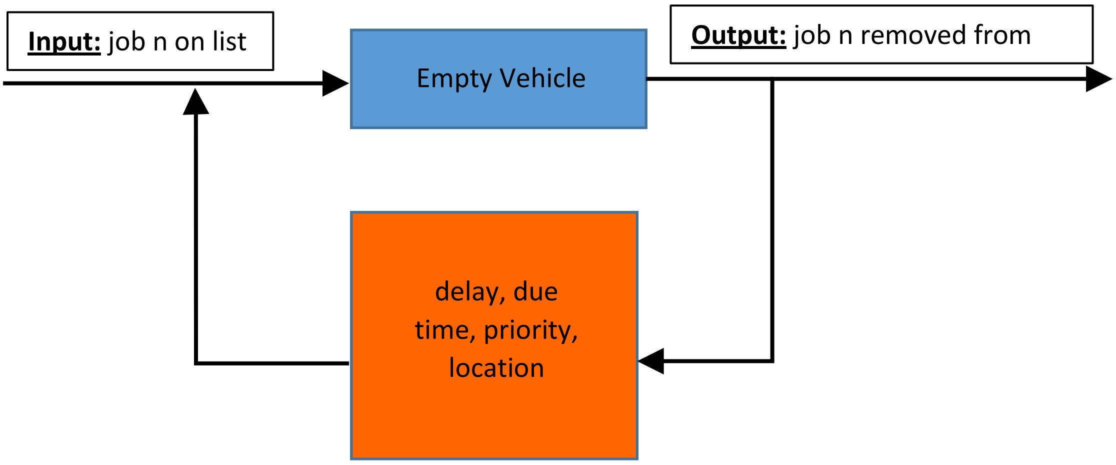


Figure 9: Feedback method for cargo shipments to increase fill rate (Van Der Heijden et al. 2005)

Material & Cost Perspectives

Material Impact Breakdown

Underground Cargo Transportation Networks are confined to experimental stages and are largely funded by independent companies, consequently there is minimal information regarding the breakdown costs. Construction costs of the tunnel system is estimated to be USD $20 million per kilometre of tunnel to $120 million per kilometre. This large range is due to numerous factors including depth of network from surface, method of construction (i.e. cut and cover, or tunnelling) and the radius of the tunnels (Verbraeck 2002; Li et al. 2016; Van Binsbergen & Bovy 2000; Ding et al. 2014). Vehicle costs as a result will fluctuate based upon the designed size, cargo mass, propulsion method, and size of fleet (Pielage 2001). Although cost isn't immediately available an approximation of the embodied energy in production and shipping of materials is an alternative to gauge associated costs of building (Table 5, Figure 10).

Software and data maintenance costs should be negligible if the network has been designed to run automatically, optimally and robustly (Van Der Heijden et al. 2005). Tunnels should be monitored frequently in comparison, with special attention to junctions and specific points depending on the cross section, as they are prone to rapid deterioration (Li et al. 2016).

Disposal costs may vary depending on the chosen method, but each having its own associated risks. Abandoning and sectioning off tunnels results in unmonitored structural degradation and may lead to drastic soil movement, unwanted in high density regions. Therefore, a costlier alternative is to backfill the tunnels and use fillings of different material compositions (Chen et al. 2010; Sivakugan et al. 2006).

Part	Material	Quantity (Mt)	Embodied Energy (MJ)	Carbon Dioxide (t)
Track	Portland Cement	2.1		
	Ready Mix Concrete	2.55		
	Aggregate	6.75		
	Rail (steel)	0.12		
	Reinforcement Bars	0.12		
	Rail Fasteners (steel)	0.12		
	Rail Pads (rubber)	~0		
		Total Track	4 million	869215
Tunnel	Ready Mix Concrete	2.55		
	Reinforcement Bars	0.12		
		Total Tunnel	3.3 million	637797
Electrical	Steel Poles	0.12		
	Contact Wire (copper)	~0		
		Total Electrical	0.4 million	69610
		Total	**7.7 million MJ**	**1576622 t**

Table 5: Material Impact Table. Source: (Chang & Kendall 2011)

Energy Mass Balance Case Study

The California high speed rail (HSR) system infrastructure case study was the closest equivalent to underground systems on a city wide scale. The underground network materials and energy inputs and outputs are similar to those of a UTS and from the analysis it is evident that there is as much energy that is invested into construction as the materials which are required to be utilized. Transportation and fuel investment of shipping heavy duty construction equipment and vehicles are aspects eluded from material evaluations which may become crucial in final costing of the project. A significant difference between the Californian HSR project is the cut and cover method and the TBM that will be used in urban construction regions. Use of the TBM will easily substitute within Figure 10 but additional costs of renting one are significantly more expensive than the cut and cover method (Mousavipour, 2015).

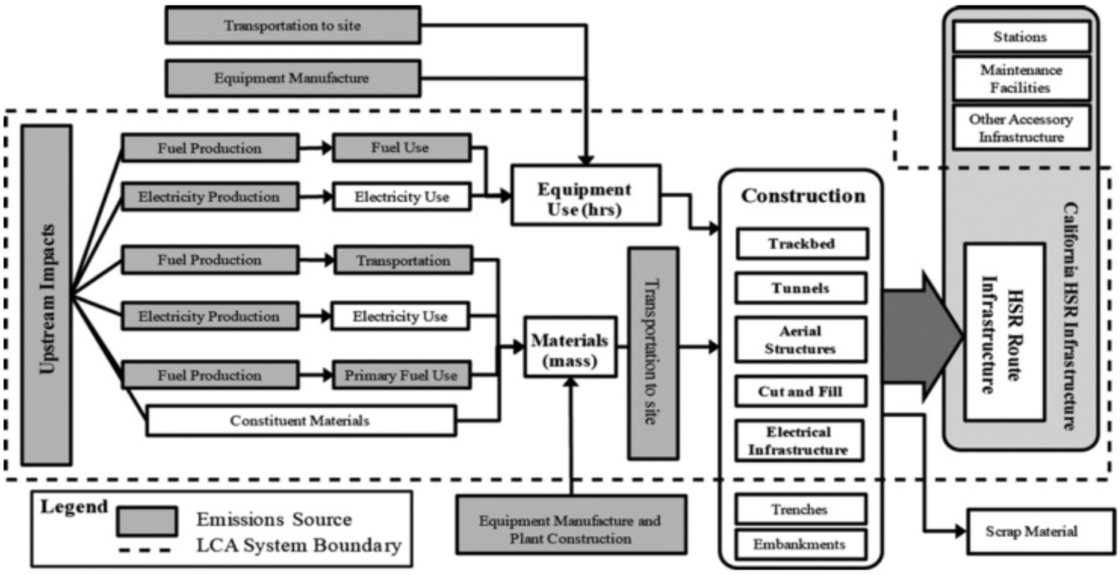


Figure 10: Energy Mass Balance of building underground networks (Chang & Kendall 2011)

Conclusion

Underground distribution systems are a long-term high cost investment with a high return for high density urban-cities with increasing populations. Most efficient network would be a highly automated system with vehicles running on LIM propulsion, with limited human interaction designed to distribute in a round trip flow. Cost is still highly varied as UTS are still within developmental stages in cities as resultant from the life-cycle costing and mass-energy balance. With increased funding and cities willing to invest in forefront technology networks to improve their cities, rapid shipping is easily available within the near future.

Recommendations

Considerations as to the degree of automation and complexity of a network requires careful planning of the variables that will be most cost effective, yet with a long term use kept in mind. Tailoring of cargo and connecting transportation is integral to effective networks and evaluation is highly advised in these circumstances. Opportunities to utilize existing tunnel networks underneath cities will significantly reduce costs and reduce construction time, in consideration of heritage listing laws.

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