A Review of Automatic Vehicle Location Technologies and Applications to Commercial Transportation

by

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B.Eng. with honors, Civil Engineering ACGI
University of London, 1993

Submitted to the Department of Civil and Environmental Engineering
in Partial Fulfillment of the Requirements for the
Degree of

MASTER OF SCIENCE
in Transportation

at the

Massachusetts Institute of Technology

May 1995

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Abstract

The purpose of this thesis is to study the available technologies for Automatic Vehicle Location (AVL) and dynamic fleet management systems and to determine the benefits of such systems in commercial transportation. The main focus of the research is on freight transportation. An AVL and dynamic fleet management system is an assembly of positioning, communication and information subsystems. The AVL subsystem determines vehicle positions. The information system integrates vehicle positions with real-time information about traffic, weather, customers' demand etc., and dynamically updates the fleet operating plan (i.e. routes, schedules, and tours or sequencing of stops) to maintain optimal operations. Communication systems are used to send vehicle positions to the control center and send back updated operating plans to the vehicles. A scan of the available AVL, communication, and information technologies is carried out. A study of the characteristics, capabilities and costs of each technology is provided. The potential benefits of the use of AVL and dynamic fleet management systems in commercial transportation are then studied. Its use is expected to improve service quality, efficiency and asset utilization. The dollar value of the benefits vary according to the type of service offered, and the effectiveness of a system in providing such benefits relies on the on the operating environment and the capability of the technologies used. Therefore, for a nonspecific case, a qualitative study of the benefits is presented. The application of AVL and dynamic fleet management systems to commercial transportation is also studied. A method that can be used by commercial carriers to select the appropriate technologies for their AVL and dynamic fleet management systems is proposed. A hypothetical case study is presented to demonstrate how this research can be used in real world applications. Finally, conclusions and suggestions for further research are provided.

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Table of Contents

List of Figures

List of Tables

1 Introduction

1.1 Purpose

To maintain their competitiveness, commercial fleet operators are constantly looking for ways to reduce costs and improve service. Furthermore, new advances in shippers' logistics management systems are increasing demand for high levels of service. Such levels of service are difficult to achieve by the traditional static planning of fleet operations. In static planning of fleet operations, the routes, schedules, and tours or sequencing of stops of vehicles are pre-planned and are not adjusted while vehicles are in operation.

Advances in communication, automatic vehicle location, and information technologies now provide the capability for fleet managers to track and control operating vehicles in real-time. An Automatic Vehicle Location (AVL) and dynamic fleet management system is expected to improve service and efficiency. Such a system has been implemented in a number of limited applications. However, the potential benefits of such systems has not been fully exploited. The purpose of this thesis is to study the available technologies and determine the potential benefits of AVL and dynamic fleet management systems in commercial transportation. The main focus of the research is on freight transportation.

1.2 Background and Motivation

Freight carriers can be divided into specialized and general freight carriers. Small parcel carriers, automobile carriers, and gasoline carriers are examples of specialized carriers. General freight carriers, which carry most categories of freight, can be divided into truckload (TL) and less-than-truckload (LTL) carriers.

Shippers choose their carriers on basis of price and the level of service. In this competitive environment, carriers' prices primarily depend on their costs. Costs are divided into capital costs (e.g. trucks and terminals) and operating costs (e.g. drivers ,fuel etc.). The level of service of a carrier is partly defined by trip time, trip time reliability, and rate of loss and damage of shipments[1]; these all directly affect the shippers' logistics costs. Issues such as flexibility, availability of equipment and service, and access to information systems, whose effect on the shippers logistics cost may be difficult to quantify, also have an impact on the level or quality of service of carriers.

Typically, providing high levels of service require higher carrier costs. High levels of service are in demand by shippers whose logistics costs are significantly affected by the level of service.

Traditionally, carriers pre-plan their operations based on given demands. However, carriers are offering services where pre-planning of operations is not feasible any more. For example, Federal Express promises a pick-up one hour after a call is placed.

Furthermore, Just-in-Time (JIT) delivery systems are being applied by manufacturers and retailers. The aim of JIT systems is to eliminate inventory and have trucks act as mobile warehouses. This requires a flexible service with high trip time reliability that is difficult to provide using a static plan. In some cases, companies, like Bose Corporation, operate their own private fleets to maintain high quality of service.

Up-to-date information about shipments is also becoming more important to the shipper. Intermodal containers carrying JIT shipments are being tracked using automatic equipment identification systems. Federal Express has a customer information system that receives around 250,000 queries a day on the status of shipments. UPS has invested in a cellular network covering the entire US to provide instant tracking information.

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[1] Martland, Carl D., A Customer's Perspective; A Logistics Framework, Jan. 1992.

Finally, hazardous material are being transported by road. Accidents involving vehicles carrying such materials, typically, result in spills or fires. Monitoring such vehicles can be used to improve public safety.

Advances in communication, Automatic Vehicle Location (AVL), and information systems have provided fleet operators with real-time information with benefits for fleet management. Knowing vehicle positions is expected to help carriers track shipments, enhance emergency response capabilities, and improve terminal management. Furthermore, a central system can be used to dynamically dispatch and route vehicles on the basis of real-time information about vehicle positions, traffic, weather and new demand. Dynamic planning is expected to reduce trip times, improve trip time reliability, and increase capacity utilization of vehicles and terminals.

1.3 Current Application of AVL and Dynamic Fleet Management

AVL and dynamic fleet management systems are frequently used in public safety functions, in particular, daily police vehicle/dispatch operations. Such systems are also used for quick parcel pick-up service, reliable Just-in-Time deliveries and shipment tracking information. The aim of this section is to breifly note the current use of AVL and dynamic fleet management systems. Examples about Detroit City emergency response system, Federal Express, UPS, and Bose Corporation are presented.

To enhance response capabilities, AVL is used to locate emergency vehicles in real-time. The location information allows fleet controllers to dispatch the nearest vehicle to the scene of an emergency. One example is the II-Morrow's Vehicle Tracking System (VTS) that is being used to dispatch emergency vehicles in Detroit. This implementation of AVL has six dispatch stations which monitor some 760 police, fire, and emergency vehicles. The vehicle tracking system allows dispatchers at computerized graphic workstations to route the nearest vehicles to the scene of an emergency.

Similar to emergency response services, parcel delivery companies are using AVL to provide quick response to pick-up calls. Real-time information about vehicle positions and new demand are used to update schedules of vehicles in operation. Federal Express and UPS fleets that serve their air service use Loran and Global Positioning Systems to locate their vehicles. A pick-up for an air package is typically carried-out within around an hour of placing the request call.

Finally, the Just-in-Time (JIT) concept is being applied by manufacturers and retailers[2]. The aim of JIT systems is to eliminate inventory and have trucks act as mobile warehouses. However, JIT systems are very time sensitive and trip time reliability of inbound shipments is a key element of its success in manufacturing. Therefore, manufacturers applying JIT systems are demanding high levels of service reliability and real-time information about shipment status. Containers and trailers carrying JIT intermodal shipments are being tracked using identification systems. Trucks carrying JIT shipments are also being tracked using AVL. Bose Corporation, a leading manufacturer of sound systems, uses an AVL and dynamic fleet management system to operate its private fleet.

Bose Corporation is based in Framingham, New England, and operates plants in Mexico, Canada and the United States. Bose's main customers are automotive manufacturers. Bose supplies and fits the sound systems into the automobiles at the customers' plants. JIT systems are applied at all the plants of Bose and its customers. The main reason why Bose decided to own and operate a fleet is to ensure high service reliability for its JIT shipments. Therefore, the primary purpose of the use of an AVL and dynamic fleet management system in this case is to maintain high trip time reliability and provide information about shipment status.

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[2] Fujita, Takako, "Challenges in Implementing the Just-In-Time System in the US Retail Industry", MIT Sloan Thesis, MS Management, May 1992, pp24.

Bose uses a satellite based system for positioning and two-way communication between vehicles and the control center. At the control center, real-time information about traffic, weather and road conditions are integrated with vehicle positions to update the vehicle routes. Traffic information is collected using telephone based services and, in some cases, from the drivers themselves.

The fleet serves the plants of Bose and its customers. Therefore, the system is not often used for dynamic dispatching. According to Bose, only about 10% of the loads are picked-up by dynamic dispatching. Most of such loads originate from suppliers located near Bose's customers. Finally, increased security is one of the additional benefits of AVL to Bose.

1.4 Scope of Research

The purpose of this research is to study the available technologies and determine the potential benefits of Automatic Vehicle Location (AVL) and dynamic fleet management systems in commercial transportation. First, the available technologies were researched. An analysis of the value of location information then identified the potential benefits of the system. Finally the application of AVL and dynamic fleet management to commercial transportation is studied.

Chapter 2 provides a review of the available technologies for an AVL and dynamic fleet management system. This part of the research is divided into three sections: AVL Technologies, Communication Technologies, and Information Technologies. Detailed description of the technologies is provided in Appendices A and B.

Chapter 3 is an analysis of the potential benefits of AVL and dynamic fleet management to commercial fleet operators. First, the value of location information (i.e. information on vehicle positions), alone, is presented. Then, the potential benefits of a dynamic fleet management system that integrates location information with real-time information about traffic, weather and new demand is described.

Chapter 4 studies the application of AVL and dynamic fleet management systems to commercial transportation. A method that can be used by carriers to select the appropriate technologies for their AVL and dynamic fleet management systems is proposed. A hypothetical case study is, also, presented as an example to demonstrate how the research of this thesis can be used for real world applications.

Chapter 5 provides the conclusion and suggestions for further research.

2 Technology Scan

This chapter scans the available technologies for Automatic Vehicle Location (AVL), communication, and information systems and studies their integration in an AVL and dynamic fleet management system. AVL systems determine vehicle positions in real-time. Information systems integrate vehicle positions with real-time information about traffic, weather, customers' demand etc., and dynamically updates the fleet operating plan to maintain optimal operations. The fleet operating plan is the vehicles' routes, schedules and assignments. Communication systems are used to send vehicle positions to the control center and send back updated plans to the vehicles.

To determine a vehicle's position, an AVL system takes a measurement or observation and converts it into position coordinates. The type of measurement varies among the different systems. For example, when Direction Finding technology is used, the relative bearing of the vehicle with respect to two or more fixed points is measured. A Direction Finder, which is a device that measures the relative bearing of a transmitter, is used to take the measurements. A transmitter is a device that radiates electromagnetic waves.

Depending on the technologies used and the system's design, measurements can be taken centrally or on-board each vehicle. When measurements are taken centrally, the in-vehicle AVL unit has a passive role, and an infrastructure is used to take the measurements. When measurements are taken on-board vehicles, the infrastructure, if any, has a passive role, and the in-vehicle AVL unit takes the measurements. For example, when Direction Finding is used, the system can be designed for measurements to be taken centrally or on-board each vehicle. When measurements are taken centrally, vehicles are equipped with transmitters and an infrastructure of fixed Direction Finders are used to measure the relative bearing of vehicles. When measurements are taken on-board vehicles, an on-board direction finder measures the relative bearings of fixed transmitters.

When measurements are taken centrally, the capacity of AVL systems (i.e. the maximum number of position fixings per interval of time) becomes significantly limited. This makes such central systems suitable for services such as locating vehicles in cases of emergency where the demand for vehicle positions per interval of time is low. However, when AVL is used to improve commercial fleet management, the demand for vehicle positions per interval of time would be considerably higher. Therefore, the technology scan concentrates on systems that carry out measurements on-board vehicles.

Measurements are then converted to 2-dimensional or 3-dimensional position coordinates. When measurements are taken centrally, conversions are carried out by a central computer system which is typically at the control center. When measurements are taken on-board vehicles, conversions can be carried out by an on-board vehicles computer or by a central computer system. Carrying out conversions centrally would limit the capacity of the system (i.e. the maximum number of position fixings per interval of time).

Real-time information about vehicle positions, traffic, weather etc. are then used by an information system to update the fleet's operating plan. This process can only be carried out centrally because, when optimizing operations for the entire fleet, information about one vehicle might alter the plan of another vehicle. A scan of the available computer software and hardware and manual systems used for dynamic fleet management is presented in the Information Technologies section.

A communication link is needed to carry information about vehicle positions to the control center and send back the updated operating plans to the vehicles. Communication systems that use different technologies are discussed in the Communication Technologies section.

Figure 2.1 describes the function of AVL, communication, and information technologies in an AVL and dynamic fleet management system. In the AVL system described in figure 2.1, measurements are taken on-board vehicles.

AVL and Dynamic Fleet Management System

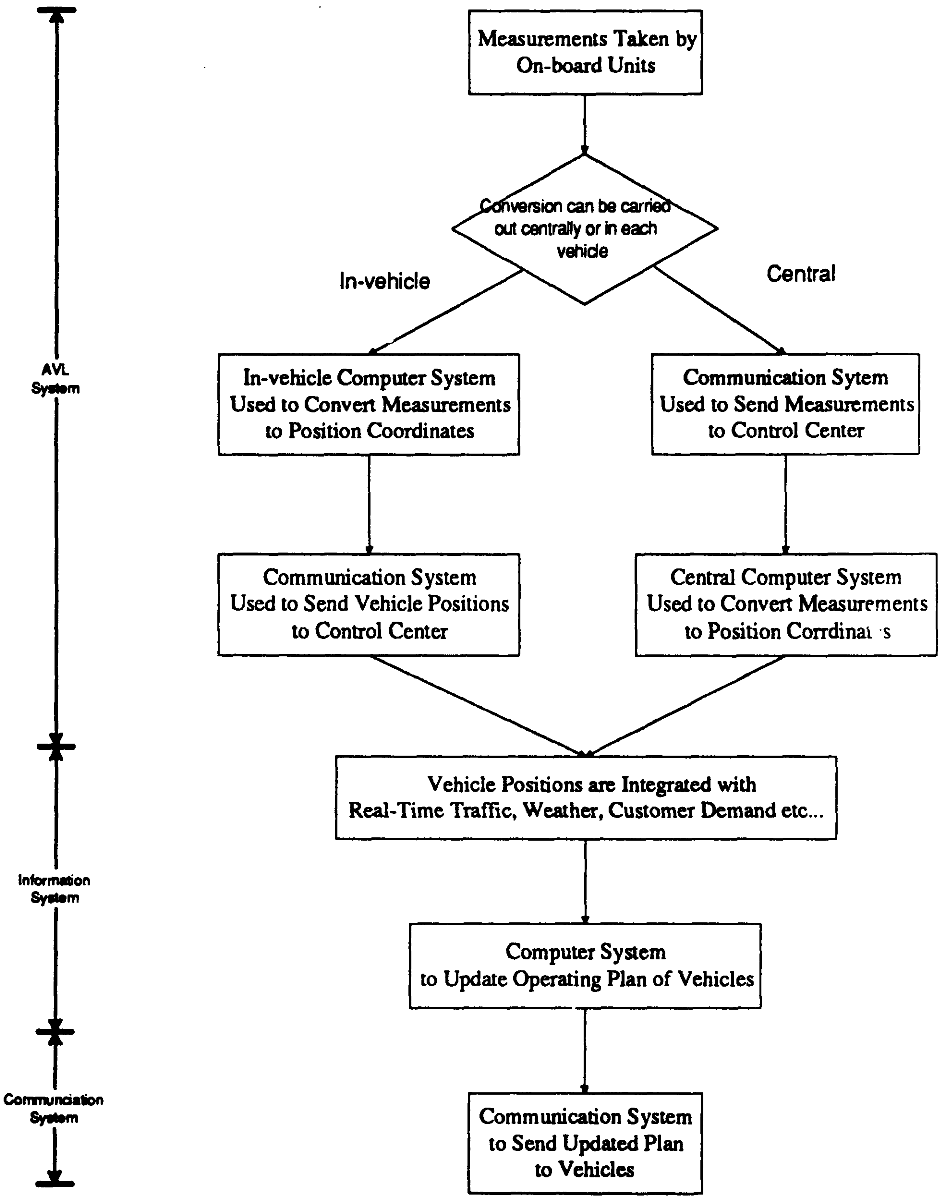

Figure 2.1

2.1 Automatic Vehicle Location (AVL) Technologies

The aim of this section is to scan the available technologies for Automatic Vehicle Location (AVL) systems. AVL systems determine vehicle positions. Eight AVL systems that use different technologies are introduced. For each system, the basic principle or idea is briefly described, and the technologies involved are presented. The main characteristics, advantages and disadvantages of each system are presented. Implemented examples of some systems are also provided. More detailed descriptionof the discussed AVL systems can be found in Appendix A. Appendix A includes eight sub-appendicies. Each sub-appendix discusses the basic principle, communication requirements, coverage, capacity, accuracy, reliability and cost of a system. Table 1 compares the different systems except for Address Reporting system. The Address Reporting system is a manual system for locating vehicles. It has unique characteristics, and cannot be compared with the rest of the automatic vehicle locating systems.

In an AVL system, the positioning process can be divided into two parts. First, observations or measurements are taken. Second, the observations or measurement are converted into vehicle positions.

Measurements can be taken on-board each vehicle or centrally. When measurements are taken centrally, the capacity of AVL systems becomes considerably limited. The thesis studies the application of AVL systems in commercial transportation where there is demand to know vehicle positions, often. Therefore, this section concentrates on AVL systems that take measurements on-board vehicles.

Identification technologies is the only type of AVL technologies introduced in this section for which both arrangements (i.e. taking measurements centrally and on-board each vehicle) are considered. The reason is that identification systems, unlike the other AVL systems, can only determine vehicle positions at discrete locations. Taking measurements centrally (i.e. by infrastructure at each location) would limit the positioning capacity at each of the locations (i.e. maximum number of vehicles that can be positioned per interval of time at each location). However, the number of vehicles that pass each location per interval of time is typically much lower than the positioning capacity when measurements are taken centrally. Therefore, when identification technologies are used, taking measurements centrally is, in many cases, as effective as taking measurements on-board vehicles.

The measurements are then converted to the position coordinates. In some cases, corrections are needed. When measurements are taken on-board vehicles, converting the measurements into position coordinates and correcting them can either be done centrally or on-board each vehicle. When measurements are taken centrally, conversions and corrections are done centrally. In comparison with on-board systems, centralized systems are typically more economical and can store larger data bases for correction. However, capacity is often limited in centralized systems.

The cost of the computers or processors that carry out the conversions is approximately similar for all the systems compared in Table 1. For this reason, the table only compares the costs of taking measurements.

Table 1

Characteristics of AVL Technologies

	Configuration	Coverage	Accuracy	Reliability	Cost
Identification (ID) Systems	ID units along vehicle routes and on-board vehicles	Area covered by roadside units	depends on the distance between roadside units	high except when pseudo-optical system is used	depends on the area of coverage
Dead Reckoning	Dead Reckoning in-vehicle units	unlimited	accuracy deteriorates with time -accuracy depends on recaliberation rate	high (Inertial systems)-low (mechanical systems)	moderate $300 (mechanical) -$500 (Inertial) per in-vehicle unit)
Direction Finding	Direction Finders (DF) and 2 or more transmitting stations	area within range of stations	depends on the distance of DF from transmitting stations	low	low ($ 50 per DF)- very high for private networks
Hyperbolic Radio Navigation Systems					
a) Decca	In-vehicle Decca units and chains of Decca Stations (Radio Towers)	area within range of a chain- Public network covers the North East of the US	low (public network)- average (private mini chains)- accuracy deteriorates with time -accuracy depends on recaliberation rate	average	low ($50 to $100 per in-vehicle Decca unit) - very high for private networks
b) Loran-C	In-vehicle Loran units and chains of Loran stations (Radio Towers)	area within range of a chain- Public network covers the entire US	average (public network)-high (private mini chain)	high	low ($100 per in-vehicle Loran unit) - very high for private networks
c) Cellular	Cellular phones and network of cell sites (Radio Towers)	area covered by cellular service used	high	high	high ($500 to $600 per cellular in-vehicle unit)
Global Positioning System	In-vehicle GPS units, 24 satellites in orbit	global/ continental	very high	high	very high ($600 to $1000 per in-vehicle unit)

2.1.1 Address Reporting

The idea of Address Reporting is that a vehicle's position can be determined on a map if the driver reports his or her address. The address of a vehicle can be reported as a street number and name or as a coded message that can be converted to a geographic position at the control center. The system can only provide information about vehicle positions at discrete times. The key characteristic of this system is that humans have a primary role in the positioning process. Therefore, it might not be technically considered an "Automatic" Vehicle Location System. However, the system can be an effective way to track vehicles and involves relatively low capital costs which may make it attractive to some carriers.

The design of the reporting system is the main factor affecting the performance of this method. The design of the reporting system includes the choice of the communication system, position calculation system which is typically centralized at the control center, and the reporting procedure.

Address reporting can be carried out by sending either voice or electronic messages. It is assumed that when voice reporting is made, position calculation is carried out manually at the control center. In case of electronic reporting, it is assumed that position calculation is carried out by a computer system.

The communication system used can either be a mobile system with terminals on-board the vehicles or a public telephone system. Public phones are typically used for voice messages only, and their use is uneconomical except in cases when very few reportings are made (around 4 reportings per day per vehicle). Otherwise, mobile systems are typically more economical because the driver can report his address when the vehicle is moving. When electronic messages are sent, the communication system is used for a shorter interval of time and position calculation is carried out using a computer system. Therefore, the use of a mobile electronic communication system, that involves higher capital costs, becomes economical when a very large number of reportings are made (e.g. around 300 per vehicle per day) especially for large fleets.

The capacity of the Address Reporting system (i.e. maximum number of reportings per interval of time) is limited by the capacity of the communication link (i.e. maximum number of users at any one time) and the capacity of the position calculation system. Therefore, when an electronic communication system is used, the positioning capacity is higher because each message uses the communication link for a shorter time in comparison to voice. Furthermore, a computer system typically has larger capacity for position calculation.

For a delivery company, an efficient way to report vehicle positions is for drivers to send a message that a certain pre-planned delivery or pickup has been made; therefore, the control center would know the address of the truck. The driver only has to send the delivery number or, in some cases, where packages are bar coded, a reading device is used to copy the bar code and send it to the control center. This makes the reporting process quicker and easier. The accuracy of the message sent to the control center is high once the driver sends the correct delivery number because the control center knows the exact address of the delivery or the pick-up. Furthermore, the control center is expected to know the sequence of deliveries and pick-ups; therefore, it is expected that any error made by the driver in entering the correct code would be detected.

Implemented Examples

In all of their services, United Parcel Services Inc. drivers report to the control center every time they make a pick-up or a delivery. The message that is sent from the driver by radio is an electronic message and includes information such as if the package has been delivered or not. When the message is received by the control center, the package can be identified and therefore the address of the delivery or the pick-up can be retrieved.

2.1.2 Identification Systems

In an identification system, identification units are installed in vehicles and along the roadside at strategic locations within the vehicles' operating area. Identification units can either be "readers" or "writers". A reader unit identifies a writer unit by reading the code of the latter. Identification can be carried out using radio wave, micro-wave, pseudo-optical scanning, and magnetic induction systems. In all systems, the reader has to be within close range of the writer for identification to take place. For example, in magnetic induction systems, roadside units have embedded loops that interact with the in-vehicle units of the vehicles passing over the loop. The in-vehicle units in magnetic induction units are typically mounted underneath the body of vehicles. The main disadvantage of identification systems is that if the route of vehicles is not fixed then the cost of covering an operating area can be extremely high. Furthermore, the system can only position vehicles at discrete places (i.e. at roadside units).

If roadside units are readers, roadside units are expected to read the code of any in-vehicle writer that passes by (Figure 2.1.2.1). Reader units of radio wave and magnetic induction systems can read the codes of more than one writer at any one time. On the other hand, micro wave readers and pseudo-optical scanners can only read the code of one writer at a time. Therefore, microwave and pseudo-optical scanning systems with roadside readers have smaller capacity. The roadside unit then sends the code of the vehicle, for example "v", along with its own code, for example "f". At the control center, the position of the roadside unit "f" is known.

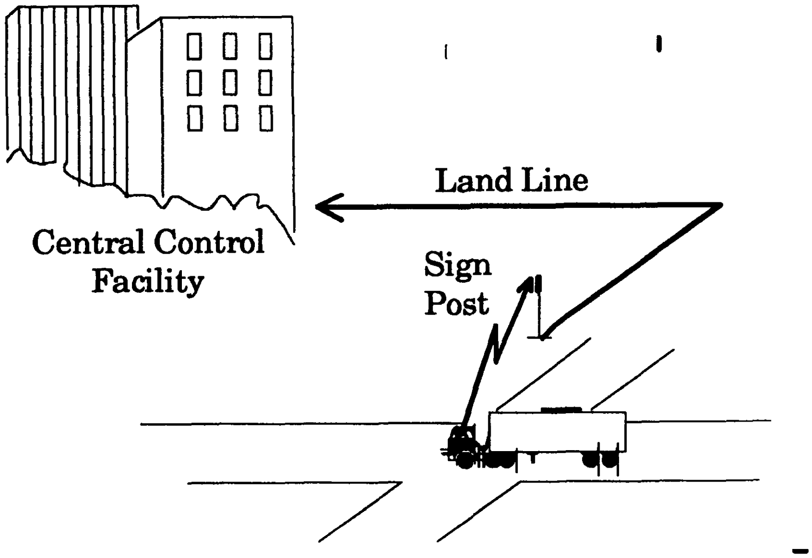

Figure 2.1.2.1

Identification system with roadside readers

When in-vehicle units are readers, in-vehicle units are expected to read the code of any roadside writer, for example "f", that the vehicle passes by (Figure 2.1.2.2). The position of the roadside unit can be determined using an on-board computer system and then the vehicle's position (same as the position of unit "f") is sent to the control center. In this case, the capacity of the system is unlimited. Otherwise, the vehicle can send its code along with the roadside unit's code, "f", to the control center where the position of "f" can then be determined using a central computer system. The capacity would be limited by the capacity of the central computer system used.

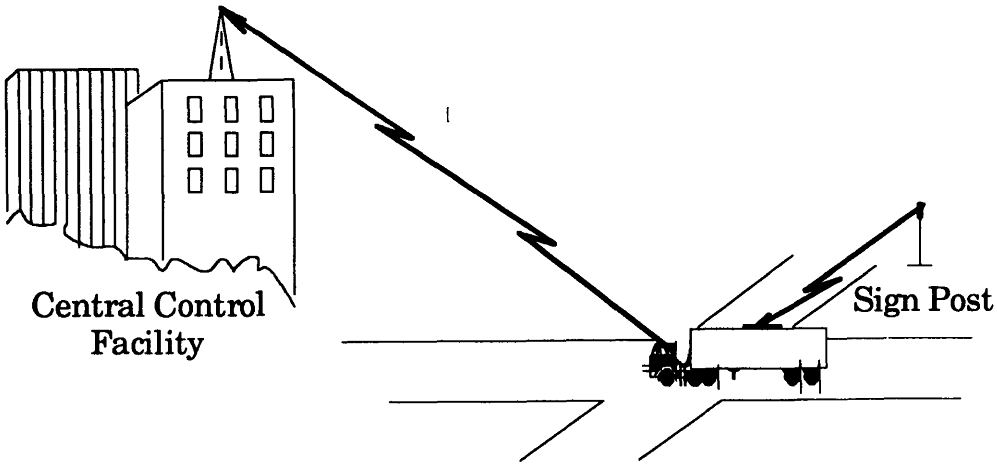

Figure 2.1.2.2

Identification system with in-vehicle readers

Identification systems can only confirm that a certain vehicle is within the range of a roadside unit. Therefore, the positioning accuracy is the range of the roadside unit. Micro-wave systems have the longest range while pseudo-optical systems have the shortest range. In magnetic induction systems the vehicle has to be on top of the embedded loop. If an identification system is used to estimate vehicle positions on a continuous time basis, then the accuracy depends on the distances between roadside units.

The system might fail to work in three cases. First, any part of the hardware or software might breakdown. Second, the vehicle might be traveling at a speed such that the time it spends within the range of a roadside unit is not adequate to complete the identification process. Third, dirt, ice or snow might cover the units. Micro-wave units are the most reliable because of their long range and the high penetrability of their signal. On the other hand, pseudo-optical beams cannot penetrate ice or dirt, for example.

A transportation carrier can own its roadside units if the appropriate licenses are available. Otherwise, a transportation carrier would have to lease existing roadside units. Hard-wire links between the roadside units and the control center are typically leased from communication companies.

Readers are typically more expensive then writers. Therefore, for large fleets that operate on fixed routes, it is more economical to have roadside reader units. On the other hand, for small fleets that have random routes, it is more economical to have the in-vehicle reader units. In general, identification systems are not economical for fleets that do not travel on fixed routes.

Implemented Examples

U.S. freight railroads have mandated that all freight cars used in interline service (i.e. more than one railroad) will be outfitted with radio frequency writer units by January 1, 1995. Identification of rail cars and locomotives is expected to increase asset utilization and improve reliability of service.

The use of identification systems in the trucking industry have been developed for trucks serving as part of intermodal chains. The purpose for truck identification was mainly to offer continuous location information for customers. In certain cases, carriers tag (i.e. install writer units on) their trailers to track them while in transit by rail.

Amtech have developed a system to track intermodal international shipments using automatic identification systems. Trucks, trailers, and containers are tagged ,and readers are fixed on factories' and warehouses' entrances and port gates. Those tags (i.e. writer units) can also be read by the reader system installed by the railroads. This system allows Amtech to track a shipment seamlessly from origin to destination[3].

2.1.3 Dead Reckoning

In Dead-Reckoning systems, a vehicle's position at the end of a time interval is determined by knowing the initial position and the displacement of the vehicle for that interval. A number of systems can be used to determine the displacement vector of a moving vehicle over an interval of time. Inertial and mechanical systems are discussed in this section. The main characteristic of Dead-Reckoning systems is that the measurements are carried out by in-vehicle units without relying on external factors except inputting the initial position. The measurements are then converted to position coordinates by using either an on-board computer system or a central system.

Using a gyroscope, the inertial system measures the vehicle's acceleration along defined angular and linear axes over an interval of time. The system has a time clock that measures the length of each interval. Knowing the velocity vector (speed and direction) and the position of the vehicle at the beginning of the interval, the length of the time interval , and the measured acceleration, the updated position and the velocity of the vehicle at the end of the time interval can be calculated. The updated position and velocity are then used as initial conditions for the following time interval. The time interval lasts as long as the vehicle is in a state of constant acceleration.

In mechanical systems, only the displacement vector (distance and direction) of a vehicle is measured. The mechanical system does not need a time clock. Given the displacement vector and the initial position of the vehicle, the position is updated whenever there is a

[3] Amtech Backscatter Winter 1993- 1994, "Amtech Links Transportation Modes for Seamless Container Tracking", pp5.

change in the direction of travel. The updated position vector can then be used as the initial position at the beginning of the next interval.

The use of updated conditions (i.e. velocity vectors and position vectors) at the end of a time interval as initial conditions for the following interval ideally implies that only one set of initial conditions is needed per vehicle. However, the main disadvantage for Dead Reckoning systems is that this process leads to the building up of errors grow with time. To keep the accuracy at a certain level, corrections to vehicle positions should be made every certain number of updates. The corrected positions would represent a new set of initial conditions. This can be done automatically by using an identification systems or an Address Reporting system. With calibration every 30 kilometers, Inertial Dead Reckoning is accurate within 25 meters or better. To further improve the accuracy of the system, map matching can be carried out. When the AVL system determines a vehicle position which is not on a road, map matching estimates its path and assigns it to the nearest road.

Gyroscopes can be easily installed on any type of vehicle while the measuring devices used in mechanical systems need to be designed to fit a certain type of vehicle. Therefore, mechanical systems are only economical when used for large fleets of standard vehicles that require the same system design. Furthermore, gyroscopes are typically more reliable.

2.1.4 Direction Finding

The basic principle of Direction Finding is that a vehicle's position can be determined by knowing the bearing of the vehicle relative to two fixed points. There are two methods for determining the relative bearing of a vehicle: 1) by using a normal receiver to listen to a fixed transmitter radiating a different signal in more than one sector, or 2) by using a Direction Finder. The light house radio beacon signal is an example of a fixed transmitter that transmits a different signal in more than one sector (i.e. frequency x MHz in the sector 90 to 100 degrees from north and y MHz in sector 100 to 120 degrees from the North).

For example, a ship equipped with a receiver can measure the received signal and deduce its relative bearing with respect to the light house. A receiver is a device that can receive and read electromagnetic wave signals.

On the other hand, the Direction Finder is a device that can determine the bearing of a transmitter. It was primarily developed for ships and planes to help them find the bearing of a port or an airport respectively relative to their position. This section concentrates on Direction Finders.

A Direction Finder consists of an antenna and an aerial system used together to determine the direction of the incoming radio waves (Figure 2.1.4.1). The direction of radio waves is the bearing of the great circle between the transmitter and receiver. The main advantage is that bearings of any transmitting station can be taken.

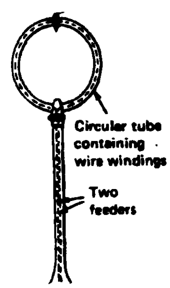

Figure 2.1.4.1

Direction Finder[4]

To fix a position, either two different bearing readings are required or a bearing reading and a distance measurement is needed. This section will only discuss position fixing of on-land vehicles using two different bearing readings. If the bearing of a transmitter is measured using two Direction Finders at known positions , then the position of the transmitter would be the intersection point of the two bearing lines. Similarly, a Direction Finder can determine its own position by finding the bearings of two fixed transmitters at known positions. Because each Direction Finder can take one measurement at a time and

[4] Sonnenberg, G.J., "Radar and Electronic Navigation", 6th edition, Butterworths, 1988, pp94, figure 3.1.

because the number of available radio frequencies is limited, it is more appropriate to have each vehicle equipped with a Direction Finder and have transmitters, with known positions, cover the operating area. In practice, three bearing readings are typically carried out to determine the position of the Direction Finder (Figure 2.1.4.2). The bearing readings are then converted into position coordinates either by using an on-board computer system or by a central computer system.

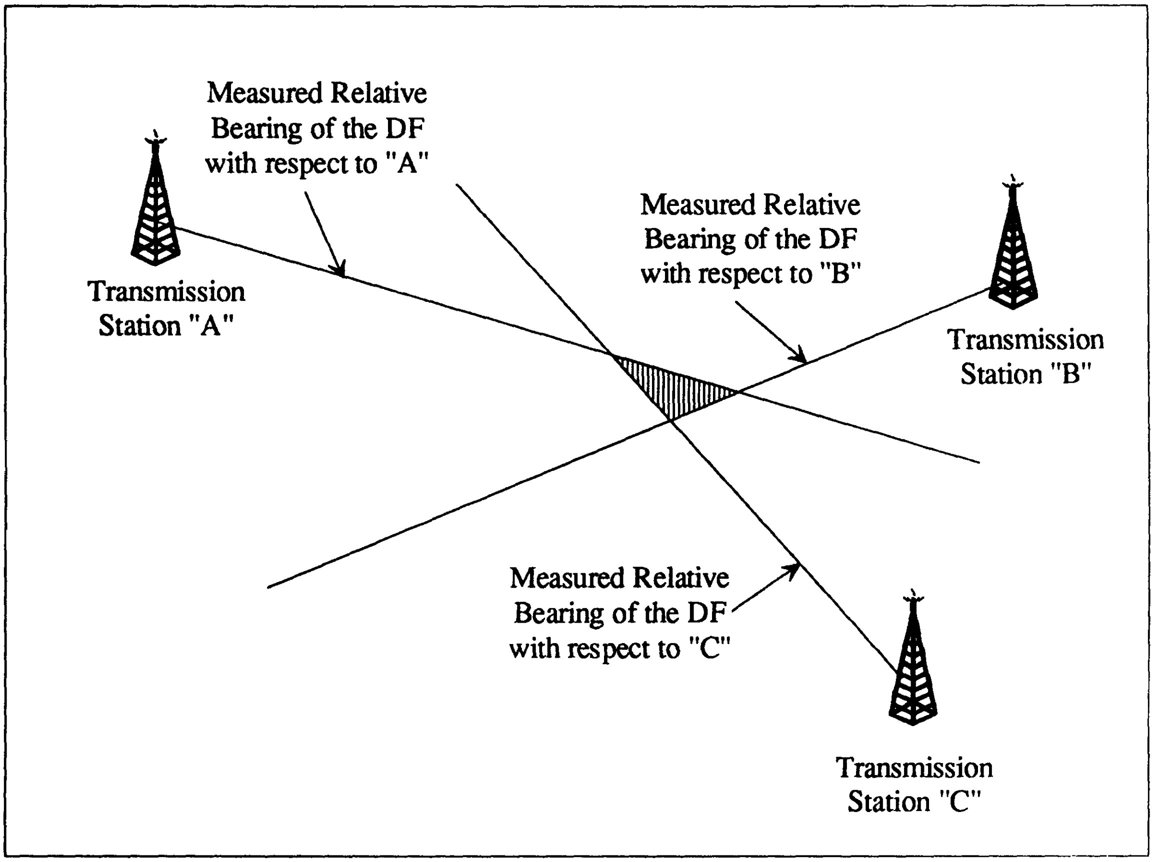

Figure 2.1.4.2

Position fixing by Direction Finder

(DF is Direction Finder and the shaded area is where the DF is located)

The position fixing inaccuracy is the product of the bearing inaccuracy and the distance between the Direction Finder and the transmitter. Therefore, the position fixing error is directly proportional to the distance between the Direction Finder and the transmitters. For high positioning accuracy, mini-chains of transmitting stations are required. The cost of the Direction Finder is very low relative to other navigational aids; however, the cost of transmitting stations is considerable. This makes mini-chains economical for large fleets operating within a relatively small geographical area. Finally, Direction Finders use motors, which are not highly reliable, to rotate the aerial.

2.1.5 Hyperbolic Radio Navigation Systems

All hyperbolic radio navigation systems are based on the principle that radio frequency energy is propagated through space with a known velocity. A measurement of the difference in times of arrival of radio signals from two points by a receiver provides a measure of the difference in the propagation paths involved. By definition, the locus of points with a constant difference in distance from two reference points is a hyperbola. It is assumed that propagation paths are straight lines. Therefore, knowing that the receiver is at a point of constant difference in distance from two reference points means that the receiver is located at a point within a hyperbolic line-of-position (Figure 2.1.5.1). Note that this hyperbolic line-of-position is two dimensional and does not describe the height of the receiver above sea level. For position fixing, at least three transmission stations are needed to draw two hyperbolic lines-of-position whose intersection would be the location of the receiver. Similarly, the position of a transmitter can be determined by measuring the time difference of the arrival of its signal at two fixed receivers. In this section, it is assumed that a receiver's position is to be determined by using fixed transmitters. This is because a mobile transmitter typically takes much more power than a mobile receiver and because a system with mobile transmitters has limited capacity. Furthermore, public systems such as Loran-C can only operate by having fixed transmitters.

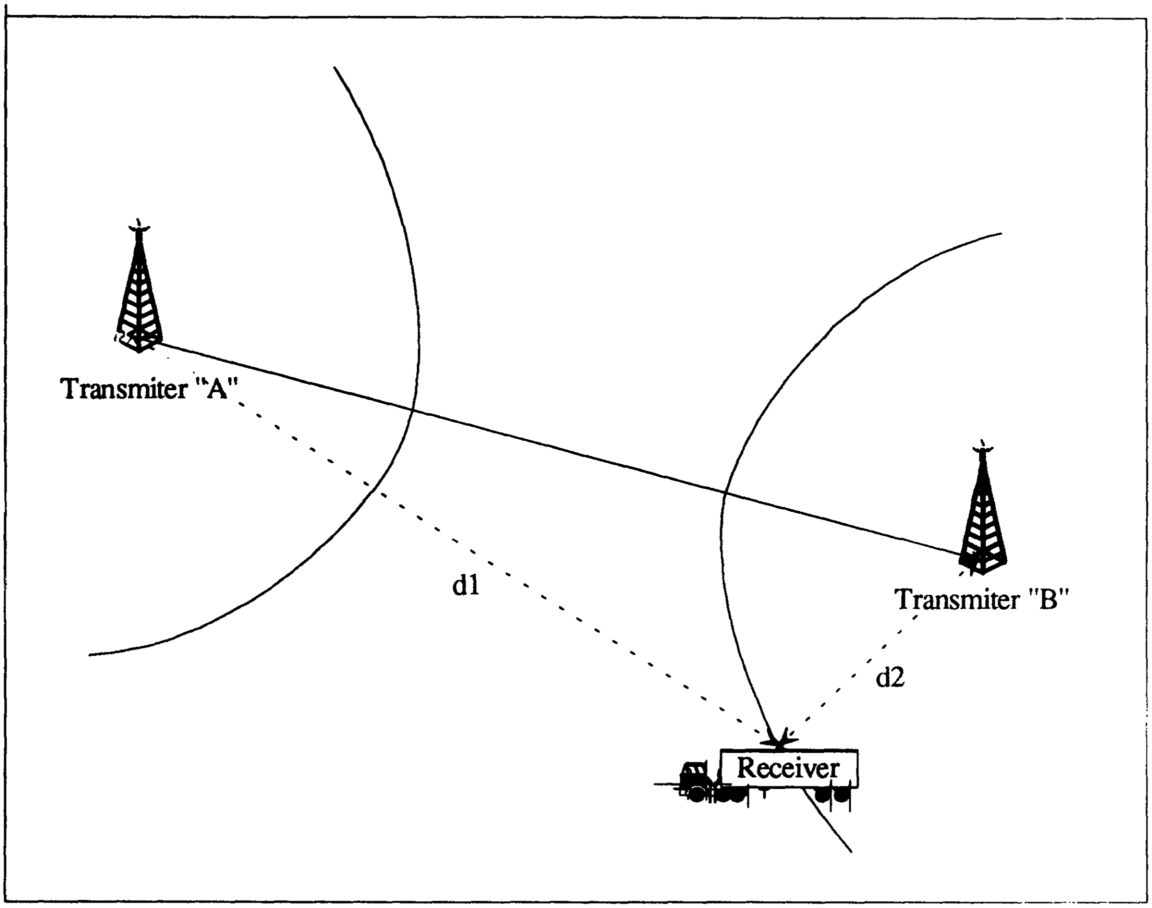

Figure 2.1.5.1

Hyperbolic line of positioning

If (d1-d2)^2 = constant, then the receiver is on a hyperbola as shown in Figure 2.5.1.1

Transmission of radio frequency energy used in hyperbolic systems ranges from unmodulated continuous waves to short pulses. The Decca system, for example, uses normal radio waves while Loran-C uses pulse emission. The difference in signal arrival times is measured by phase and pulse matching in case of pulse emission systems and by phase matching in case of continuous normal wave systems. However, in case of normal wave systems, the phase difference would be the same for any two positions whose separating distance is a factor of the wave length. A counter that can read the number of complete of complete wavelengths can be used to overcome this problem. Therefore, the difference of the signal arrival times would be the sum of the phase difference and the number of complete wave lengths counted by the counter. However, such a continuous system typically leads to the building up of errors that might become time divergent.

The hyperbola by definition is two continuous sets points (branches) symmetrical to a straight line (figure 2.1.5.1). Using the counter in the normal wave systems would determine which side of the hyperbola the receiver is on. In pulse emission systems, one of the pair of transmitting stations used to draw the hyperbola starts transmitting only after it receives the signal of the other station. This would clarify which branch of the hyperbola the receiver is on. Now, it can be assumed that the line-of-position is a branch of the hyperbola. Therefore, the maximum number of intersection points between two lines-of-position is two points. When long range hyperbolic systems are used, it is typically obvious which of the two points is the position of the vehicle; therefore two lines-of-position are enough to determine the position of the receiver. Shorter range networks can be designed in a way that one of the intersection points would be automatically dropped out. For example, the transmitting stations can be situated in a way that only one intersection point between any two lines-of-position fall in the operating area of vehicles. To verify the position of the receiver and ideally attain one common intersection point, three different hyperbolic lines-of-position are needed.

Furthermore, even if the position of a vehicle can be identified among more than one intersection point, having an extra line-of-position helps increase the accuracy of the position coordinates of the receiver. Due to inaccuracies, common intersection points between more than two hyperbolic lines-of-position might not coincide. In this case, the position of the receiver would be the within the area enclosed by such intersection points. Figure 2.1.5.2 shows an intersection point between three lines of position. Sections 2.1.5.1, 2.1.5.2, and 2.1.5.3 present Decca, Loran-C and Cellular systems that are all hyperbolic systems.

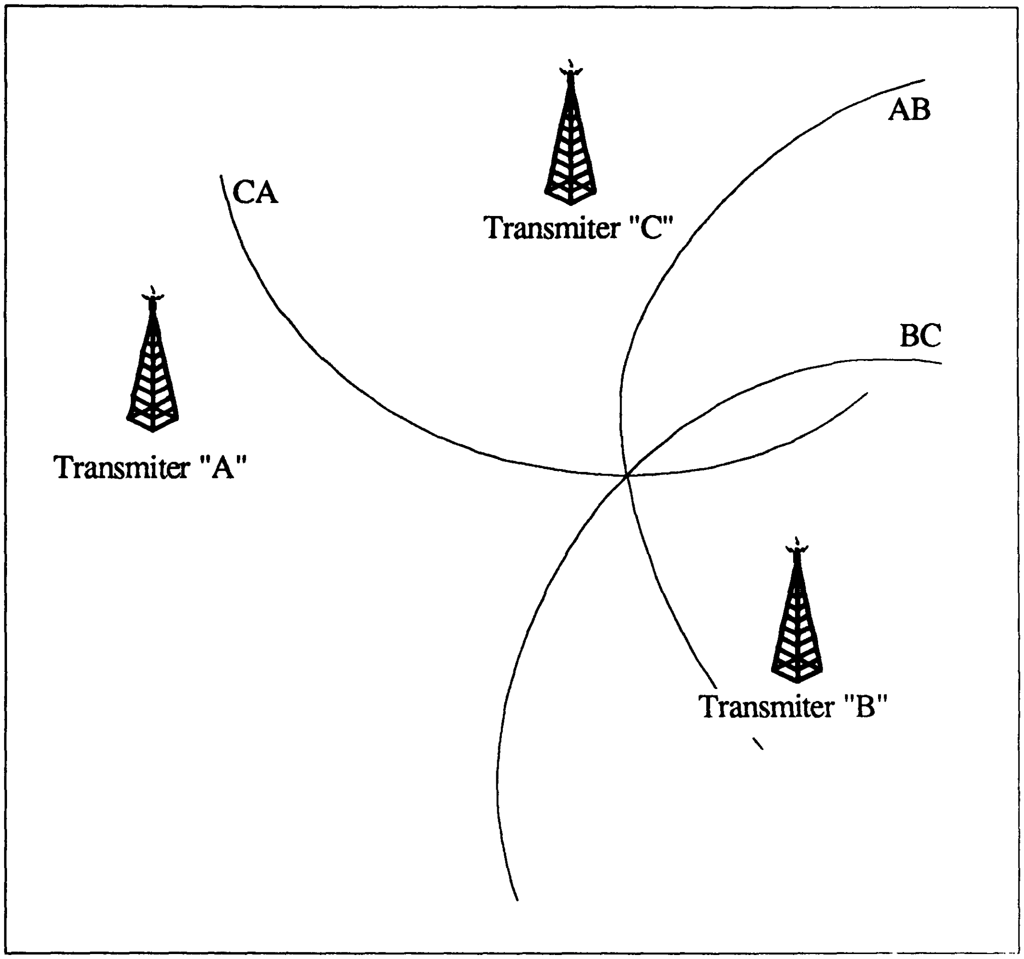

Figure 2.1.5.2

Position fixing using a hyperbolic system

2.1.5.1 Decca System

In a Decca system, four transmitting stations are used to determine the location of a special receiver on-board a vehicle. The receiver has three indicators, decometers, whose dials are distinguished by colored knobs. One of the transmitting stations is a master station and the rest are slaves. Decca transmission stations are installed in different parts of the world offering the Decca system signals for free. This public network covers the north eastern part of the United States. A transportation carrier can build its own mini-chain to accommodate his needs.

Each slave station transmits continuously at a constant frequency. The master station includes a receiver that reads the frequencies of the slave stations. The master station matches the frequency of a slave station and the phase difference of the received voltage at the vehicle is measured by the Decometer. Each decometer reads the phase difference in the voltage of between the received waves of the master station and one of the slave stations (Figure 2.1.5.1.1). A counter that can read the number of complete revolutions of each dial (i.e. number of complete wave lengths in units time) is used. Therefore, the difference in signal arrival time at each decometer would be the sum of the counted wave lengths and the measured phase difference. The counter would also allow the user to identify which branch of the hyperbola is the line-of-position.

Using the readings of the three decometers, three lines-of-position can be drawn. The possible locations of the receiver are the intersection points of the lines-of-position. It is typically easy to identify which of the intersection points is the real location of the receiver. Lines-of-positions and intersection points can be determined using a central or an on-board computer system.

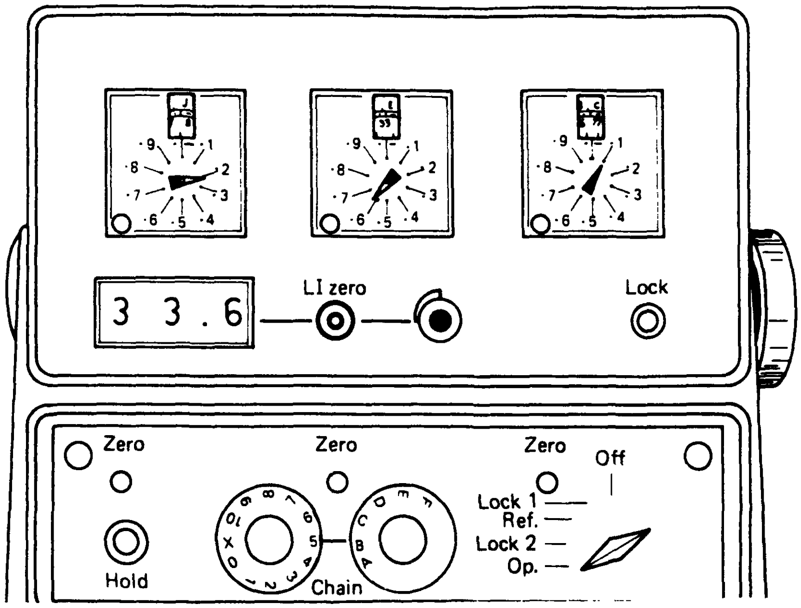

Figure 2.1.5.1.1a

Decca Receiver[5]

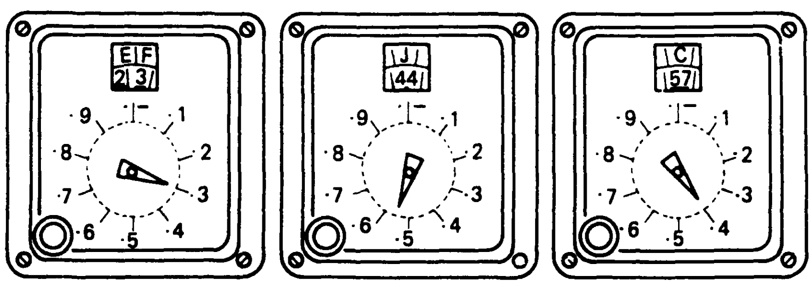

Figure 2.1.5.1.1b

Decometers[6]

Decca receivers are cheaper than Loran and Cellular receivers. However, the use of continuous radio waves makes the Decca system an open loop system with time divergent errors. Other systems such as Address Reporting and Identification systems can be

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[5] Sonnenberg, G.J., "Radar and Electronic Navigation", 6th edition, Butterworths, 1988, pp153 Figure 4.22.

[6] [6] Sonnenberg, G.J., "Radar and Electronic Navigation", 6th edition, Butterworths, 1988, pp153 Figure 4.23.

incorporated to maintain a certain level of accuracy. Furthermore, using mini-chains will improve accuracy. However, the cost of setting up mini-chains is high.

2.1.5.2 Loran-C System

The term Loran is derived from the descriptive phrase LOng RAnge Navigation. The Loran system was primarily developed as a marine and aircraft navigational aid. Loran-C is an advanced version of the older Loran systems, Loran-A and Loran-B, and was developed to meet operational requirements for greater accuracy and greater service range.

All Loran systems provide navigational-fix data in the form of hyperbolic lines-of-position determined by the time differences between the reception of pulse signals from widely separated transmitting stations. Long range Loran networks whose signal reach most of the United States and other regions around the world have already been installed for marine navigation and their use is open to public. However, a Loran mini-chain, that typically yield more accuracy, can be installed to cover a limited geographic area.

The technical principle that distinguishes Loran systems from other hyperbolic radio navigation systems is the use of pulse emissions. This permits the unambiguous measurement of time difference of signals from different transmitting stations and further provides the means for discrimination at the receiving location between ground waves and sky waves.

A Loran-C system consists of chains of transmitting stations. A Loran-C chain consists of a master and up to four secondary or slave stations. Each secondary station transmits a group of pulses at a certain frequency. The master station matches the frequencies of the secondary stations one at a time. Because the receiver cannot distinguish between the master's and the salve's signal, the slave transmission station starts transmitting only after it receives the master's signal. The receiver, therefore, reads the master's signal first and then the slave's signal and determines the time difference by pulse and cycle matching. In addition to determining the hyperbola, this allows the receiver to determine which branch of the hyperbola is the its line-of-position. One of the advantages of pulse transmission is that when the received pulses overlap which leads to a less accurate time difference measurement, a coded delay can be incorporated in transmission to avoid any overlap. This coded delay is accounted for in the time difference measurement.

For on-land vehicle position fixing, Loran-C receivers are installed in vehicles to measure signal arrival time differences. The measured time differences are then converted to lines-of-position and position coordinates by a computer system. This computer system can either be installed on-board each vehicle or can be a central system serving a fleet of vehicles. Figure 2.1.5.2.1 shows a Loran-C receiver that includes a computer system to determine position coordinates.

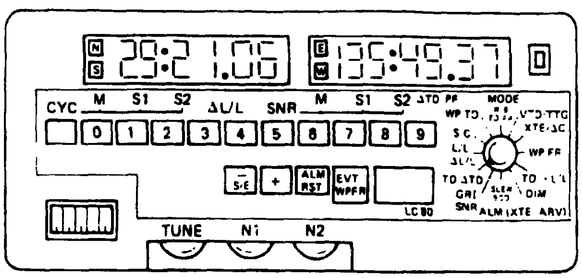

Figure 2.1.5.2.1

Loran-C Receiver[7]

Loran-C systems, which are more accurate than Decca systems, provide a position fixing with an average error of 500 meters[8]. Loran receivers are much cheaper than GPS

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[7] [7] Sonnenberg, G.J., "Radar and Electronic Navigation", 6th edition, Butterworths, 1988, pp185 Figure 5.14.

[8] Sonnenberg, G.J., "Radar and Electronic Navigation", 6th edition, Butterworths, 1988, pp177.

receivers. However, setting up a mini-chain to attain a high accuracy (around 50 meters) is very expensive. Therefore, mini-chains would only be economical for large fleets operating in a relatively small area. Otherwise, Loran-C would be suitable for carriers that need national coverage and are not in need for high accuracy.

2.1.5.3 Radio Cellular System

A cellular phone system can be modified to operate as a hyperbolic positioning system as well as a communication system. In a cellular phone system, each transmission station, cell site, provides a number of available channels for cellular phone users to use within its coverage area. The use of radio cellular systems for communication is discussed in the Communication Technologies chapter. When used for communication, the receiver of the mobile phones measures the strength of signals from a number of cell sites. The mobile phone automatically switches to and uses the frequency of the cell site with the strongest signal. Two different cellular systems are available, the digital and the analog systems. Digital systems use pulse signals while analog systems uses normal wave signals. Normal wave signals are continuous signals, while pulse signals are signals with very short duration. In the U.S., the analog system is currently used while the digital system is still being developed. The digital system is currently in use in Europe.

For positioning, adjacent cell sites are required to have certain frequencies in common. Having the mobile receiver read the common frequency, the difference in arrival times of the signals of any two adjacent cell sites can then be measured. In an analog system, in addition to using cycle matching to measure the phase difference between the received signals, a counter is used to count the complete number of wave lengths traveled through. The difference in signal arrival times would be the sum of the counted wave lengths and the measured phase difference. Similar to Decca systems, a cellular analog system is a continuous positioning system whose errors build up with time. Digital systems are closed loop, the difference of signal arrival times would be determined independently for each reading by cycle and pulse matching. To determine which branch of the hyperbolae is the line-of-position, one of each pair of cell sites should only transmit after receiving the signal of the other cell site.

Cellular phone system for a fleet of trucks is expensive. However, the analog and digital cellular systems provide the same fixing accuracy as a Loran mini-chain and a Decca mini-chain respectively. It is typically not economical for small fleets, that need high fixing accuracy, to set up their own Loran or Decca mini-chain. Therefore, the cellular system is suitable for such small fleets operating within areas covered by cellular phone service.

2.1.6 Global Positioning System

The Global Positioning System (GPS) uses satellite technology to provide real time positioning service. The GPS system can be divided into three parts: the satellites, the control system, and the users.

GPS has 24 satellites orbiting the earth at a velocity of around 3.9 km/sec and at an altitude of about 20,200 km. All satellites have a propulsion system to maintain orbit position and stability control (Figure 2.1.6.1). GPS satellites transmit signals to users on or near the surface of earth. The signals are then processed into position coordinates.

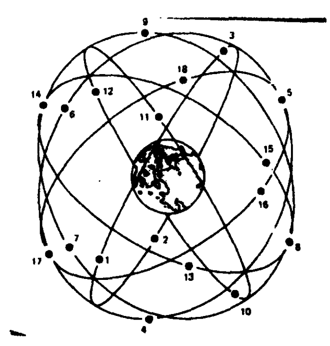

Figure 2.1.6.1

Configuration of GPS satellites

The control system includes a master control station and a number of monitor stations spread around the world. The master station includes all the information about satellites from the monitor stations that track the satellites when in "view".

The user system is a GPS receiver/processor capable of receiving at least four satellite signals simultaneously and sequentially. The receiver/processor will select which four satellites to track to provide the best geometry for position fixing. As the satellites continue their orbits, the receiver/processor will drop a satellite as soon as different satellite with better geometry becomes available. The GPS receiver/processor is very expensive (average around $800).

The main advantages of GPS is that it provides worldwide coverage and three dimensional position fixing (longitude, latitude, and altitude above sea level). Furthermore, due to having signals from four satellites with the best available geometry to each receiver, GPS's positioning accuracy is around 10 meters[9] for the general users (C/A code users) which is better than all real time continuous positioning systems. The system is typically suitable for carriers that need high fixing accuracy for their vehicles around the world.

Differential GPS (DGPS) systems are systems that evaluate GPS errors over certain areas and provide corrections for these errors for GPS users within those areas. A DGPS system needs a fixed GPS receiver/processor and an electronic data communication link to send corrections to GPS users. There are companies that provide DGPS corrections to the public using FM radio waves. A transportation carrier can also set up a DGPS system that provides corrections for the operation area of its fleet. DGPS improves the accuracy to less than 5 meters[10].

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[9] Rockwell, "Fleet Master",Company Brochure.
[10] Rockwell, "Fleet Master",Company Brochure.

2.1.7 Summary of AVL Technologies

Section 2.1 presented eight systems for locating vehicles: Address Reporting, Identification Systems, Dead Reckoning, Direction Finding, Hyperbolic Radio Navigation Systems (Decca, Loran-C, and Cellular), and Global Positioning Systems. The following is a summary of the presented systems.

In Address Reporting, the driver uses a communication link to report his or her address. The key characteristic of the system is that reporting is carried out manually by drivers. The system provides vehicle positions at discrete times.

Identification systems locate vehicles at discrete places. When a vehicle passes by a roadside unit, identification is carried out. Therefore, the vehicle position is determined to be within the range of the roadside unit. Identification systems are economical when routes of vehicles are fixed.

Dead Reckoning systems use a gyroscope or a compass and an odometer to track distance and direction of travel from a known starting point. The main problem is that errors build up with time and recalibration is needed to maintain a certain accuracy. The main advantage of the system is that all measurements are taken in vehicle without relying on any external factors.

Direction Finders are used to determine the direction of transmitter. If a Direction Finder is installed in a vehicle, the relative bearing of the vehicle with respect to two or more fixed transmitters can be determined. The position of the vehicle is the intersection of the bearing lines. The cost of the Direction Finders is very low. However, they are not highly reliable. Accuracy of the system can be considerably increased by using mini-chains of transmitters that involve high capital costs.

Hyperbolic Radio Navigation Systems use radio signals to measure the difference in distances between an in-vehicle receiver and two or more fixed transmitters. The location of the vehicle can then be determined. The Decca, Loran-C and Cellular systems are introduced.

Decca receivers are the cheapest among hyperbolic systems. The main disadvantage is that the use of continuos radio waves leads to the building up of errors with time. Therefore, to maintain a certain accuracy recaliberation is needed. Decca public network covers the north eastern part of the United States. Mini-chains can be set-up to attain high accuracy; however, they typically require a substantial capital cost.

Loran systems use pulse signal instead of continuous wave signals. This results in better accuracy (around 500 meter). The Loran public network covers most of the United States. Accuracy can be increased to 50 meters by using mini-chains of transmitters. However, the capital cost involved in setting up a mini-chain is substantial.

Cellular phone systems can be used as a hyperbolic system for position fixing. The signal of the transmission stations (cell sites) can be used to determine the position of a cellular phone. Cell sites typically have short range. Therefore, the system is similar to a mini-chain system with high accuracy. The cost of cellular phones is relatively high (average around $500).

The Global Positioning System (GPS) uses satellites to determine the position of GPS receivers. Coverage is global and accuracy is very high (10 meters). Differential GPS is offered for some areas to further improve accuracy to less than 5 meters. The cost of a GPS receiver/processor is very high (average around $800).

After presenting the different AVL technologies in section 2.1, section 2.2 will presents the different communication technologies.

2.2 Communication Technologies

In an AVL and dynamic fleet management system, a communication link is needed to send information about vehicle positions to the control center and to send back updated operating plans. It can also be used to send additional information such as mechanical conditicn, the on-board load status, fuel etc.

The advances in communication science has resulted in a range of communication technologies or systems. This section presents a number of different technologies that could be used in an AVL and dynamic fleet management system. For each technology, a general description is provided along with the systems problems, positives and applicability to AVL. The coverage, availability of service, information transmission capability, mobility, and cost of each system are then discussed in Appendix B. Table 2 compares the different communication systems.

Table 2

Characteristics of Communication Systems

	Coverage	Availability of Service	Information Transmission Capability	Mobility	Cost
Hard-Line Telephone	area covered by telephone networks	depends on the distance between public phones or centers	two-way voice and electronic messages	not mobile	low (cost of using thc service)
Paging Systems	area covered by service used- (national service exist)	high	one-way short electronic or voice messages	very high	average ($500 per pager and $20 per pager per year)
Two-Way Radio	depends on the coverage of the land bases used	low (public networks)- high (private network)	two-way voice and electronic messages	high	average ($500 per vehicle and $20 per vehicle per year)- very high for private networks
Radio Cellular Telephone	depends on the coverage of service used	high	two-way voice and electronic messages	high	$400 per vehicle and $130 per vehicle per year
Mobile Satellite System	global or continental	high	two-way voice and electronic messages	high	very high $5000 per vehicle and $600 per vehicle per year

2.2.1 Hard-Line Telephone

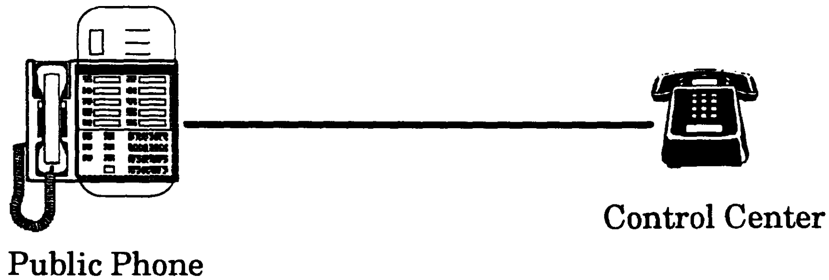

Figure 2.2.1.1

Hard-line telephone system

Information can be exchanged between driver and control center is through a hard-wired telephone system. The driver can stop at a public telephone or a telephone center set up by the carrier, and contact the control center (Figure 2.2.1.1). For example, UPS drivers report to their center or facility twice a day using public phones. The system does not require the carrier to have any infrastructure; however, the cost per call is relatively high. The system is, therefore, economical when the number of calls made is small. The main disadvantage of this system is that, for communication to take place, the driver has to call the control center. The driver, also, has to get out of the vehicle every time he makes a call. Therefore, if the control center needs to contact drivers, other systems such as a paging system has to be used. The driver also has to find a public phone to make a call. In rural areas, public phones may not be available. Furthermore, very few public phones are equipped with fax machines and/or data heads for electronic messages. Finally, the characteristics of the system makes its application in AVL systems limited to Address Reporting.

Hard-line telephone connections can also be used to link roadside "readers", in an identification system to the control center (Figure 2.2.1.2).

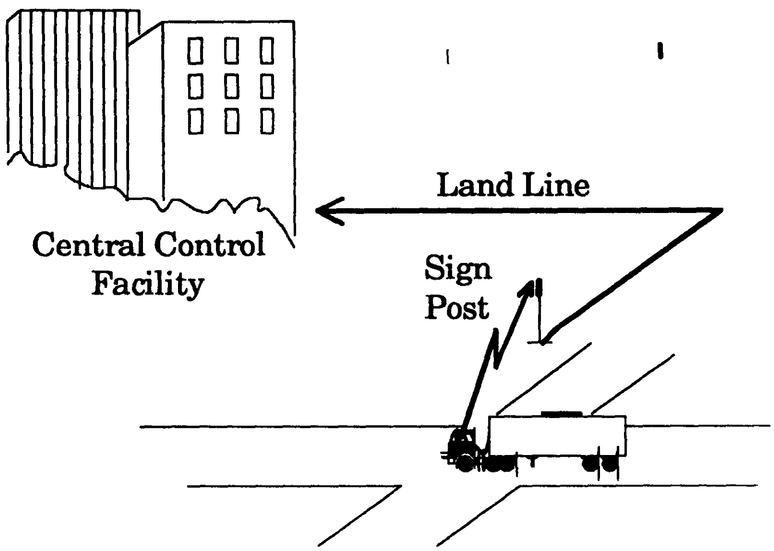

Figure 2.2.1.2

Identification system with roadside readers

2.2.2 Paging Systems

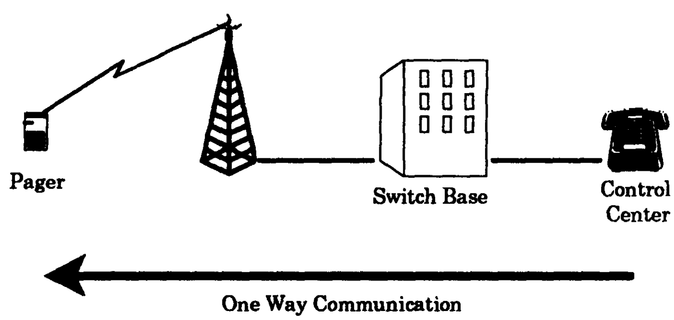

Figure 2.2.3.1

Paging system

A paging system provides means of sending messages from a telephone to a pager user at all times within a certain geographic area. The telephone call is made to the pager's switching base which forwards the message to the pager. The switching base is typically linked to transmitter bases by hard-line or radio connections, and the transmitter bases send the message to the pager through electromagnetic radio waves (Figure 2.2.3.1).

Paging services are often provided by private companies for a fee. The main advantage of the system is that pagers are small and can be easily carried by the driver. Therefore, unlike Hard-Line and Identification systems, the control center can send messages to its drivers at any time. The cost of pagers is relatively cheap. However, paging systems only allows for short messages; therefore, when a long message needs to be delivered to the driver, the paged message typically requests the driver to phone the control center. Furthermore, pagers cannot be used to send information from the vehicle to the control center. Therefore, for an AVL system, another link from vehicles to the control center needs to be used when a Paging system is used.

2.2.3 Two-Way Radio Systems

Two way radio systems operate by radiating electromagnetic radio waves between terminals to convey messages. Each terminal includes a transmitter, a receiver, and a communication terminal for voice and/or electronic data and can be either fixed or mobile. Using a special interface unit, in-vehicle units can be used to automatically send information from in-vehicle AVL units to the control center. A land base includes a transmitters and a receiver and has a wider range of coverage. Land bases act as a link between the in-vehicle units and the fixed terminal at the control center when direct communication is not possible. The land base (i.e. radio tower) can be linked to the control center by radio waves or hard-wire connections while communication between land bases and mobile terminals is by radio waves only.

To cover a wider area, a system can have several bases controlled remotely by a central base through hardwire. Radio systems can be either : Private, Shared, or Public. If a public network is used, then the cost of the system is relatively low because it only involves the cost of the radio terminals.

However, owning or sharing an infra-structure of land bases requires substantial investment and is only economical for large fleets operating in an area not covered by a public network. The main disadvantage of radio systems is that when voice is used for communication, the capacity of the system is often reached resulting in poor availability of service decreases. Also, the clarity of voice communication in Two-Way Radio systems is very low.

2.2.4 Radio Cellular Telephones

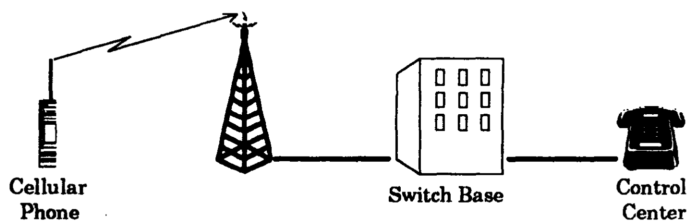

Figure 2.2.5.1

Radio Cellular phone system

A radio cellular phone system is a radio system developed to function as a telephone. It provides two-way voice and electronic messages. Information from in-vehicle AVL units can be automatically supplied to the control center. Radio cellular phones operate only within the range of radio land bases that are called cell sites. The area covered by a cell site is called a cell. The cell sites are linked to a switch base through hardwire. This switch base would provide a link to other cellular phones through the cell site nearest to the phone or to the public telephone network through hardwire (Figure 2.2.5.1).

The radio cellular phone system is similar to the two-way radio system in concept. However, cellular phone systems usually provide a better quality service at a higher cost. First, the cellular phones have access to the public telephone networks, in addition to other cellular phones, through the switch board, while a radio terminal can only contact another radio terminal or a telephone machine linked to the land base by hard-wire. Second, each cell site provides a number of available channels for cellular phone users to use within its cell. The system's main characteristic is that the range of the cell sites is kept shorter than the range of the land bases in the two-radio system which would provide better availability and capacity of service as explained in the *Availability of Service section* in Appendix B.5.

Adjacent cell sites provide different sets of available channels; therefore, as the mobile phone crosses from one cell into any adjacent cell, it switches channels automatically which causes a discontinuity in transmission. This discontinuity might not affect voice communication but would affect electronic data communication, as explained in the *Information Transmission Capability* section in Appendix B.5.

2.2.5 Mobile Satellite Systems

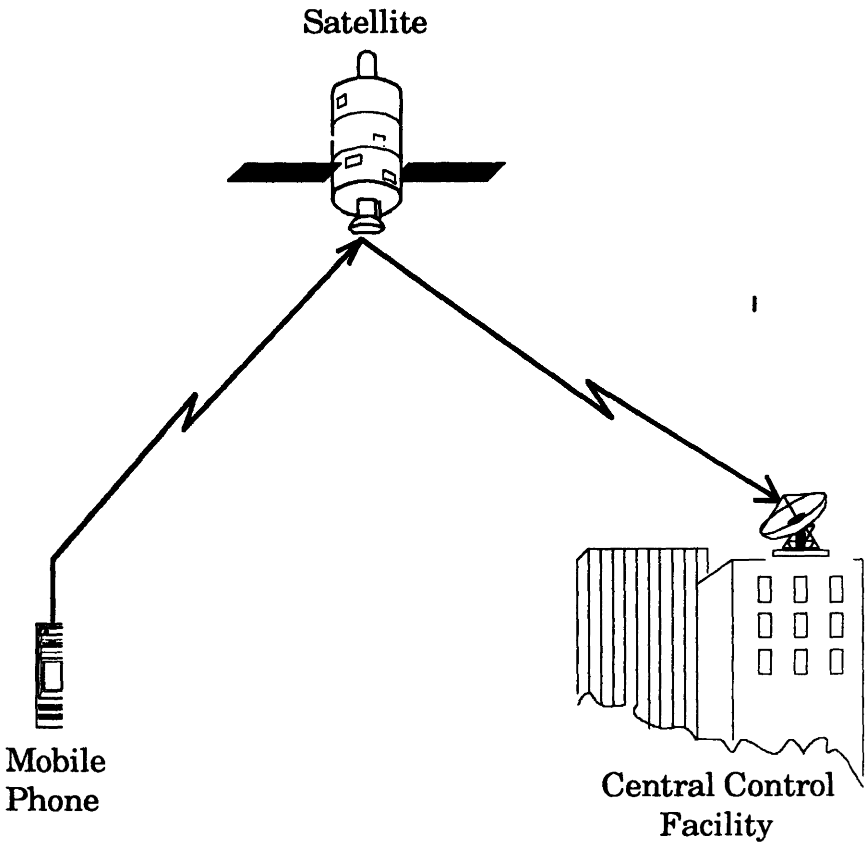

Figure 2.2.6.1

Mobile Satellite system

Mobile satellite systems allow international mobile phone service. The satellites provide a link between the cellular-like mobile phones and other mobile phones or stations equipped with satellite dishes (e.g. the central control faciltity in Figure 2.2.6.1). The system's service is similar to that of cellular phones but with international or continental coverage with no gaps. The technology was initially developed for location information and then further developed for voice and data communication. The service is typically provided by private companies in return of a relatively high fee. This system is only suitable to use with a GPS system to provide global coverage or coverage of remote areas that are not covered by any other system. Otherwise, in any other operating environment, Cellular or Two-Way Radio systems, that are cheaper, can replace the Mobile Satellite system.

2.2.7 Summary of Communication Technologies

Section 2.2 presented six communication systems: Hard-Line Telephone, Identification, Paging, Two-Way Radio, Radio Cellular Phone and Mobile Satellite systems. The following is a summary of the presented systems.

Hard-Line telephone systems can be used to exchange information between drivers and control center. The driver can use a public phone or a telephone center to phone the control center. In this system, the control center cannot reach the drivers at any time and has to wait for their calls. In identification systems, hard-line telephone connections are typically used to connect roadside readers with control center.

Paging systems provides one-way communication from the control center to the drivers. Pagers can be easily carried by drivers at all times and are designed to receive short electronic or voice messages. The cost of the system is cheap and national coverage is available.

Two-Way Radio systems provide communication between mobile terminals on-board vehicles and the control center. Voice and electronic messages can be transmitted through the system. Carriers can set-up their private networks or can use public networks. The capacity of public networks is low; therefore, the availability of service is poor. Private networks provide high availability of service; however, their costs are high.

Radio cellular telephone services provide two-way communication between mobile phones and the control center. The system can transmit electronic and voice messages. The availability of service of such systems is high; however, their costs is relatively high.

Mobile Satellite Systems use Satellites to provide two-way communication between telephones on-board vehicles and the control center. Electronic and voice messages can be transmitted through the system. The system provides continental and, in some cases, global coverage. The cost of the system is very high.

After presenting the different communication systems in section 2.2, section 2.3 presents the available information technologies.

2.3 Information Technologies

In a vehicle monitoring and fleet management system, real-time information about traffic, weather, new demand for shipments, vehicle positions, load status (e.g. empty, full, partially full etc.) and contents of each vehicle, and in some cases mechanical condition and fuel etc. are provided at the control center. The task of the information system is to process this information to reduce costs and improve service among other reasons. The information system can be used to track shipments, control drivers and improve safety and security of operations. Furthermore, it can be used to maintain optimal operations by dynamically updating the fleet's operating plan according to changes in traffic, weather and demand. For example, to maintain optimal travel costs between nodes, vehicles can be re-routed according to real-time traffic and weather conditions. Also, assignments can be re-scheduled according to new demand to reduce costs or to minimize waiting time of customers.

Information systems are typically based on computer systems. However, in transportation operation management, its tasks can be carried out manually by dispatchers who are some times supported by a computer system. Manual systems are effective in managing small fleets. For example, taxi cab dispatchers manually assign taxis to demands. For this reason, this chapters introduces both computer and manual systems.

Ideally, in both manual and computer systems, the real-time information can be received in any form (i.e. voice or electronic messages). However, if messages are received electronically, then the control center must have a computer terminal to receive such messages. This computer terminal can, typically, be used as the hardware for a computer information system. In this case, the cost of the computer information system would only be the cost of software. Therefore, in this chapter, it is assumed that when data is communicated electronically, a computer information system is used.

2.3.1 Manual Systems

In manual systems, the dispatcher typically has a map of the operating area on which the available real-time information about vehicle positions, new demand, traffic and weather is superimposed. The dispatcher then uses the map and the available information to dynamically track shipments, route vehicles, and schedule pickups and deliveries.

Except for some Address Reporting systems, all AVL systems use electronic communication to supply vehicle positions to the control center. Since, it is assumed that manual systems are only used when all information is received by fax or voice, the use of manual systems is limited to Address Reporting system that use fax or voice communication.

Ideally, dispatchers can track shipments by recording the pickups and deliveries made. This can be done for a small fleet providing truckload or less-than-truckload service where few pickups and deliveries are made per vehicle. However, it is very difficult to manually track shipments served by a large fleet and where a large number of pickups and deliveries are made per vehicle (e.g. in the order of 200 pickups and deliveries per day).

Ideally, for dynamic routing and scheduling, the optimal route (e.g. minimum cost or travel time etc.) between any two nodes within the operating area need to be obtainable. If the resistance (i.e. travel cost or time) between adjacent nodes is known, optimal routes between any two nodes can be determined using the shortest path algorithm. Given real-time traffic and weather information, resistance between adjacent nodes can be calculated if information such as distances between nodes, traffic lights, stop signs, restriction on roads (e.g. one-way streets vertical clearance, speed limits etc.) are included on the map. Given optimal routes between nodes, vehicle positions, and information about new demand, vehicle schedules can be updated to improve operating plans (e.g. reduction in customer waiting time or costs).

However, information such as traffic lights and stop signs cannot be included on a map. Therefore, the resistance (cost or time of travel) between adjacent nodes cannot be accurately estimated. Furthermore, even if the resistance between adjacent nodes is given, most dispatchers do not have the time nor knowledge to apply the shortest path algorithm to determine the optimal routes between nodes. In real situations, dispatchers rely on their experience in routing and scheduling vehicles. In simple cases, their solutions might be optimal. However, in complicated networks, finding the optimal path between two nodes is often non-trivial. Furthermore, scheduling of pickups and deliveries is a more complex problem that is more difficult for dispatchers to solve.

The performance of the manual system depends on the experience of the dispatcher and his knowledge of the operating area, size of fleet, intensity of operations (e.g. number of shipments per vehicle per day), and the complexity of the network.

2.3.2 Computer Systems

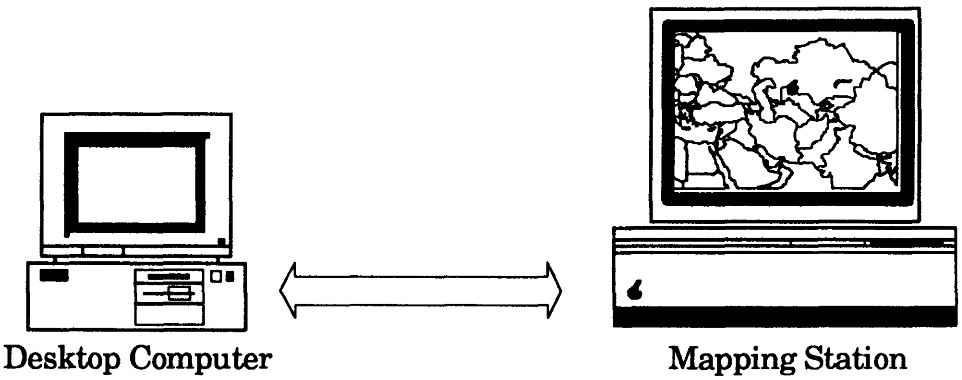

Figure 2.3.2.1

Computer Information System

In a computer information system, information can either be received electronically or by fax or voice. When information is received by voice or fax, it is entered by an employee into the computer system. Electronic data is automatically received by the computer system using a modem. The computer hardware needed is a personal computer. Software for most transportation operations management problems are available. For example, labor performance, shipment tracking, emergency response[11], routing and scheduling software all have been developed[12]. Figure 2.3.2.1 shows a typical computer information system.

Labor performance software aim at measuring and comparing the performance of different drivers using data on vehicle positions and speed, number of pickups and deliveries made, and traffic and weather conditions.

[11] Rockwell, "FleetMaster",Company Brochure.

[12] Roadnet Technologies Inc., "System Data, Roadnet 5000 P/S", Company Brochure.

Routing software aim at finding the optimal route between nodes. The routing systems use real-time traffic and weather information and Geographic Information Systems (GIS) data.

Information about traffic conditions on road networks is available at traffic control centers, and can be provided to fleet dispatchers. TRANSCOM (Transportation Operations Coordinating Committee) has undertaken a demonstration of providing fleet dispatchers with real-time traffic information on the road network of New York/New Jersey metropolitan area. When an incident takes place, TRANSCOM uses a paging system to transmit a message to the trucking companies, giving the location of the incident and a coded description as well as estimated time to clear. When the incident is cleared, TRANSCOM provides a clear message with an indication of the extent of residual delays.

The GIS data are digitized maps that include information about traffic lights , stop signs, road restrictions etc.. Therefore, the resistance (i.e. travel cost or time) between the adjacent nodes can be accurately determined. Consequently, optimal route between any-two nodes can be determined using the shortest path algorithm. GIS data are usually available on CD-ROM. If some areas are not covered by a GIS system, then digitized maps can be created from paper maps and additional information can be loaded on to the map.

New demands typically arrive in the form of addresses. Given each customer's address, most software are typically capable of calculating its geographic coordinates. Vehicle positions, optimal routes between nodes and new demands are then used to optimally schedule pickups and deliveries using Computer-Aided Dispatch (CAD) software. In case of emergency, knowing the vehicle positions and the optimal routes (minimum travel time) between any two nodes, simple computer programs can identify the vehicle that should be dispatched in order to minimize waiting time of the vehicle in distress.

The main advantage of computer systems is their high speed capability. This makes dynamic optimal routing and scheduling practically attainable even for complex detailed networks such as city roads. For example, a PC can easily handle a network with about 200,000 node and can compare tens of thousands of routing paths.

Because routing and scheduling are geographic in nature, most software provide maps and graphical displays[13]. Maps and graphical displays can be provided on the same computer or on a dedicated mapping station (Figure 2.3.2.1). Graphic displays typically shows customers and route segments superimposed on maps. Information about the vehicle's load status (i.e. full or half full etc.) and time windows for pickups and deliveries can be shown in graphical form. Finally, some software provide the capability to manipulate certain aspects of the solution in graphical form. For example, it may be useful to construct a route manually through graphical interface.

Compared to manual systems, computer systems have a much higher capital costs. However, for large fleets, savings resulting from optimal solutions are considerable and are expected to pay-off the capital costs in a short period of time.

2.3 Summary of Information Technologies

Information systems are divided into manual and computer systems.

In manual systems, dispatchers manually track, route and dispatch vehicles. This system can only be used with Address Reporting. It is suitable for small fleets operating on a simple network. Otherwise, it is not fast nor accurate enough to find, in real-time, the optimal routes and schedules of large fleets operating in a complicated network.

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[13] Jones, Jaqueline, " AVL/GPS: Find it Now", Intelligent Highway Systems, September 26, 1994 pp4.

In computer systems, computer hardware and software is used to track, route and dispatch vehicles in real-time. Its main advantage is its high speed and accuracy in finding the optimal solutions in real-time. The system can easily handle operations of large fleets in a complicated network (e.g. up to 200,000 nodes). Graphic displays can also be provided to allow manual manipulation of results. Its capital cost is high; however, it is economical to use for large fleets.

After presenting the available, AVL, communication, and information technologies, section 2.4 discusses the integration of the different technologies in an AVL and dynamic fleet management systems.

2.4 Integration of Technologies

An AVL and dynamic fleet management system is an assembly of AVL, communication and information subsystems. The available AVL, communication and information technologies have been presented in sections 2.1, 2.2 and 2.3 respectively. However, the integration of these technologies has not been discussed yet. For example, technologies for the different subsystems can be incompatible while others can share the same hardware. Furthermore, more than one technology is sometimes used for the same subsystem. The aim of this section is study the integration of technologies in an AVL and dynamic fleet management system.

First, a summary of the roles of the different subsystems is presented. Second, the integration of several technologies in the same subsystem is discussed. Third, the relationship between the choice of technologies for the different subsystems is discussed.

The role of the AVL subsystem is to determine vehicle positions in real time. The positioning process is divided into two parts. First, a measurement is taken. Second, the measurements are converted into vehicle positions. Measurements can be taken centrally or on-board each vehicle. When measurements are taken on-board vehicles, converting them into vehicle positions can either be carried out centrally, typically at the control center, or on-board each vehicle. When measurements are taken centrally, conversions are carried out centrally.

The role of the communication subsystem is to carry information about vehicle positions to the control center and send back updated operating plans to the vehicles. When measurements are converted into vehicle positions at the control center, the communication subsystem is used to send the measurements to the control center. When measurements are converted into vehicle positions on-board each vehicle, the communication subsystem is used to send position coordinates to the control center.

The role of the information subsystem is to integrate vehicle positions with real time information about traffic, weather, customer demand etc. and dynamically update the fleet operating plan to maintain optimal operations.

In each subsystem, one or a combination of technologies can be used to fulfill the role of the subsystem.

In the AVL subsystem, each of the technologies presented in section 2.1 can determine vehicle positions in real time. However, the accuracy of the Dead Reckoning, Decca, and Radio Cellular (analog) positioning technologies deteriorates with time. Therefore to maintain a certain level of accuracy, another AVL technology is required to recaliberate vehicle positions every interval of time. Address Reporting and identification technologies are typically used for recaliberation.

In the communication subsystem, hard-line telephone can be used for communication between drivers and the control centers (through public phones) and between roadside readers of identification systems and the control center.

When hard-line telephone is used for communication between drivers and the control center, it provides two-way communication that can send vehicle positions to the control center and send back updated operating plans to the driver. However, in this case, the control center cannot reach the drivers at any time. Paging systems are typically integrated with hard-line telephone to allow the control center to contact drivers at all times.

When hard-line telephone is used in identification systems as a link between roadside readers and the control center, information is sent one way form the reader to the control center. In this case, another communication technology is required to carry updated operating plans to the drivers.

Two-way radio, radio cellular telephone, or mobile satellite communication technologies can fulfill the role of the communication subsystem in an AVL and dynamic fleet management system. Nevertheless, in some cases, using a combination of these technologies is more economical. For example radio cellular telephone are cheaper than mobile satellite system. Therefore, for continental coverage, a carrier might find that a combination of satellite and cellular based technologies that switches to cellular whenever possible is more economical than using satellite based technologies at all times.

In an AVL and dynamic fleet management system, the choice of technologies for the different subsystems is closely linked.

The communication subsystem takes information about vehicle positions from the AVL subsystem and sends it to the control center. Therefore, the communication technology is required to be compatible with the AVL technologies used. In Appendix A, the communication requirements for each AVL technology has been studied. From this perspective, the AVL technologies can be divided into three groups.

The first group which only includes Address Reporting is compatible with all communication technologies.

The second group includes identification systems with roadside readers. This group requires a communication system that automatically sends identification information form the roadside reader to the control center. Roadside readers are fixed; therefore, hard-line telephone communication systems are typically used. A special interface unit is used to intake information from the reader. The cost of such interface units is listed with costs of communication technologies in Appendix B.

The third group includes identification systems with in-vehicle readers and Dead Reckoning, Direction Finding, Hyperbolic Radio Navigation, and Global Positioning systems. This group requires a communication system that automatically takes information from in-vehicle AVL unit and sends it to the control center. The communication technologies compatible with this group are two-way radio, radio cellular telephone, and mobile satellite systems. Such communication systems can be equipped with data terminals for electronic communication and special interface units to intake information from AVL units.

While, some technologies are incompatible, other technologies can share the same hardware. If the communication system is used for electronic communication, then the control center must have a computer system. The hardware of this computer system can be shared by the communication and the information subsystems. Therefore, the cost of a computer information system would be limited to the cost of software. In this case, a computer information system is typically installed.

After providing a technology scan for an AVL and dynamic fleet management system in chapter three, chapter four discusses the benefits of such systems.

3 Benefits of AVL and Dynamic Fleet Management

Chapter 2 presented the available technologies that can be used in an AVL and dynamic fleet management system and studied their costs, characteristics and capabilities. When a commercial carrier considers installing an AVL and dynamic fleet management system, the decision wheather or not to install the system is made by comparing the costs and benefits of the system. This chapter aims at presenting the benefits of AVL and dynamic fleet management to commercial carriers.

AVL and dynamic fleet management systems are expected to reduce costs and/or improve the level or quality of service (e.g. speed and reliability of pick-ups and deliveries, customer information system etc.) of carriers. The effectiveness of an AVL and dynamic fleet management system in providing such benefits relies on the operating environment (e.g. urban/intercity, concentration of the fleet's vehicles in their operating area, mean distance between adjacent roads etc.) and the capabilities of the technologies used (e.g. position fixing accuracy of AVL technology).

Furthermore, the dollar value of the benefits vary according to the type of service offered. For example, the value of safety of operations for a carrier specializing in transportation of hazardous material would be greatest among the other benefits. On the other hand, a carrier serving Just-in-Time shipments, for example, would find trip time reliability of greater value than safety.

Therefore, ideally, for a specific case (i.e. given the operating environment and the type of service offered), the gain of using an AVL and dynamic fleet management system can be estimated and compared to the cost of the system. However, for a nonspecific case, the benefits of AVL and dynamic fleet management to commercial carriers can only be studied qualitatively. This chapter provides a qualitative study of the benefits of AVL and dynamic fleet management.

In an AVL and dynamic fleet management system, vehicle positions are determined by the AVL technology and sent to the control center. Information about vehicle positions is referred to as location information. At the control center, location information, alone, is used to set up information systems, control drivers, improve safety and security of shipments, and improve terminal management. The benefits of location information are discussed in section 3.1.

Furthermore, location information can be integrated with real-time information about traffic and weather conditions and new demand to dynamically update the fleet's operating plan (i.e. routes, schedules, and assignments). This is referred to as dynamic fleet management. Dynamic fleet management will improve reliability of pickups and deliveries. It will also increase capacity utilization of vehicles and reduce trip times. A carrier might use the improvements in trip times and capacity utilization to provide quicker deliveries and pickups (i.e. higher level of service) without expanding the fleet or to provide the same service with fewer vehicles (i.e. at a lower costs). Benefits of dynamic fleet management are studied in section 3.2.

3.1 Benefits of Location Information

This section presents the benefits of location information to commercial carriers.

3.1.1 Customer Information System

Shipment tracking information is becoming increasingly important for shippers. In the parcel delivery service, Federal Express receives 250,000 queries a day on status of shipments. Also, manufacturers receiving Just-in-Time (JIT) shipments often demand shipment tracking information. JIT systems are applied by manufacturers to improve production efficiency and eliminate inventory. Received shipments are unloaded directly onto the assembly line. Therefore, up to date information about arrival times of JIT shipments is crucial for scheduling the operations of the assembly line.

AVL can be used to determine the positions of vehicles, containers, and trailers. Therefore shipments on-board vehicles and trailers or in containers can be easily tracked by carriers. Tracking containers and trailers would allow for the tracking of intermodal shipments. Furthermore, knowing shipment positions and paths in real-time, the arrival times of shipments at their destinations can be continuously updated. A customer information system can be set-up to access real-time information about shipments. This can be used by carriers as a marketing tool.

3.1.2 Safety and Security

Vehicles can get hi-jacked or stolen. This, often, endangers drivers and can result in the loss of the vehicle and shipments on-board. This might cost the carrier the price of the vehicle, shipments on-board, and transporting new shipments to the owners of the lost shipments. The shippers would also suffer from the resulting delay which might lead to loss of revenues. Such costs are considerable when high value goods such as computers are stolen.

Knowing information about vehicle positions in real-time would help reduce hi-jacking and theft of vehicles. First, any vehicle diverting from a scheduled route can be detected, and an alert from the dispatcher to the police would help initiate a rapid search. Second, a hi-jacked vehicle would become very difficult to hide if its on-board AVL unit remained activated. Therefore, AVL would help reduce costs that may result from theft or hi-jacking for both the carrier and the shipper and increase safety of drivers. It will also attract shippers of high value goods. Also, hijackers may be deterred from these illegal acts because of the presence of AVL systems. Therefore, the frequency of hijacking incidence might decrease which might decrease insurance costs.

Finally, AVL would also improve drivers' and public safety in case of accidents. First, an accident can be quickly detected using an AVL system. For example, if a vehicle has an accident while traveling on a highway, the fleet controller will be aware the stopping of the vehicle. In such situations, communication attempts with drivers would help verify the situation. Second, AVL would determine the location of the accident instantaneously. Early detection of accidents and determination of their location would enhance the response of rescue teams. Furthermore, hazardous materials are often transported by commercial vehicles (e.g. gasoline and liquefied petroleum gas). Some trucks are even used to haul radio-active and very hazardous chemical materials. Accidents involving such vehicles often lead to spills or release of the hazardous material on-board. Knowing the location of the accident, protective measures can be taken in a faster and more effective manner.

3.1.3 Control of Drivers

Currently, there are two methods to measure and control drivers' performance other than AVL. First, inspectors can be hired by carriers. The inspectors would randomly call on vehicles and manually measure the driver's performance. However, the cost of inspectors is high, and carriers cannot afford to hire enough inspectors to monitor all drivers. Furthermore, an inspector can only take simple measurements like travel times between stops.

Second, a computerized system can be used to monitor drivers' performance. This includes a device on-board vehicles that monitors and records information about speed, idle time, braking, engine rpm, and fuel economy. The information is downloaded at the end of the day and driver's performance is evaluated. Although the system can measure drivers' performance with high accuracy, it does not allow real-time control of drivers.

AVL systems would supply the control center with real-time information about vehicle positions and speeds. Information about braking, engine rpm, and fuel economy can also be sent through the communication system that is used for AVL. This enables the carrier to more accurately monitor and control drivers' performance in real-time. The information from AVL systems can be saved in data files, and the productivity of different drivers can then be compared.

3.1.4 Terminal Management

Terminals are setup by carriers to sort and consolidate LTL shipments for long haul movements. Some terminals are also used to relay intermodal shipments between vehicles and trains, ships and planes.

Knowing the positions and paths of inbound shipments (i.e. shipments on the way to the terminal) in real-time, their arrival time at the terminal can be continuously updated. Up-to-date information about shipment arrival times can be used to improve labor, equipment and space management at the terminal. It can also be used to update schedules of outbound trips.

Also, vehicle or shipment positions can be saved in data files. The arrival and departure times of vehicles to and from the terminals can be automatically recorded by AVL. Such information is typically registered manually. Manual archiving is slow and inaccurate. AVL would carry such a task with greater efficiency and accuracy. This expected to reduce the time vehicles spend at terminals, reduce errors which, for example, might lead to sending shipments to wrong destinations, and eliminate the need for attendants that carry out the exit and entrance paperwork.

3.2 Benefits of Dynamic Fleet Management Using AVL

Traditionally, carriers have pre-planned the schedules and routes of their vehicles on the basis of a set of static assumptions such as constant travel times between known demands. However, the dynamic nature of external factors such as traffic and weather conditions and shippers needs may cause sub-optimal performance if this static operating plan is not adjusted. The aim of this section is to study the potential benefits of dynamic fleet management using real-time information about vehicle positions, traffic, weather, new demand etc.

Relative to static planning, dynamic fleet management would improve trip times, trip time reliability, and asset utilization. It would also allow carriers to provide a flexible service at reasonable cost.

3.2.1 Trip Time

The significant components of the carriers' costs, such as capital cost of vehicles and driver wages, are typically a function of time; therefore, the optimal route for cost minimization would often be that with the minimum travel time.

To optimize (i.e. minimize travel time) the routing of a vehicle between two nodes in a network, the travel times between adjacent nodes need to be known. The shortest path algorithm can then be applied to determine the optimal route.

When routing is pre-planned, estimates of travel times between nodes are typically developed using historical data on travel times. Deterministic factors such as time of day or seasons etc. are usually considered in these estimates.

However, traffic flows and travel times are affected by countless factors that are, in many cases, random. For example, accidents, broken down traffic lights, or unexpected storms etc. can all unpredictably result in deviations form the estimated travel times. In such cases, the pre-planned routing may no longer be optimal.

The frequency and magnitude of the unexpected deviations (typically delays) depend, primarily, on the operating environment (e.g. weather, size of roads, congestion levels etc.). For example, accidents are more likely to occur in foggy weather relative to clear weather. Also, the resulting delay of an accident in a narrow street, for example, is likely to cause more delay relative to an accident in a wider, assuming same traffic volume. In general, unexpected delays on roads can range from several minutes to several hours. Also, long delays are typically less frequent than shorter delays.

Traffic flows on many roads are constantly being monitored, and real-time traffic information is provided by traffic control centers. The real-time information would provide accurate estimates of travel times especially for the routes the vehicles are or soon going to be traveling on. Real-time weather information is also provided. This would improve estimates of travel times on routes that are not covered by the traffic monitoring systems. For example, knowing that there is fog or snow on a certain route helps estimate travel times more accurately.

Knowing the real-time positions of vehicle using AVL and traffic and weather information, the optimal route to the upcoming destination of each vehicle starting from the current position of the vehicle can be dynamically updated. This method of routing is expected to minimize the travel time of vehicles. The travel times of vehicles routed dynamically by an AVL and dynamic fleet management system will usually be less than or at worst equal to their travel times if their routes were pre-planned using constant travel time estimates.

The effectiveness of an AVL and dynamic fleet management system in reducing trip times by dynamic routing relies on the operating environment (e.g. frequency and magnitude of unexpected delays, mean distance between adjacent roads etc.), the traffic information provided (e.g. number of roads monitored), and the capabilities of the technologies used (e.g. the position fixing accuracy of the AVL technology used).

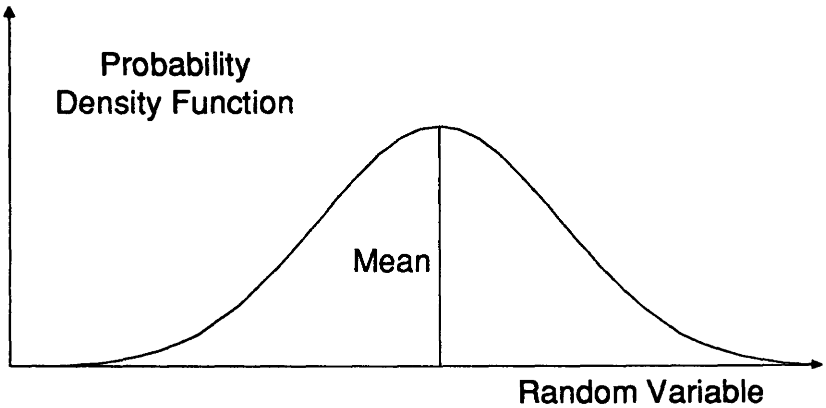
As the frequency and magnitude of unexpected delays increase, trip time reductions due to dynamic routing would become more substantial. Furthermore, as the ratio of the position fixing accuracy of the AVL technology used to the mean distance between adjacent roads decrease, the AVL and dynamic fleet management system is expected to be more effective in reducing trip times by dynamic routing. Finally, as accuracy of the information system in determining shortest paths is increased, trip time reductions would be greater.

A reduction in trip time would allow for increased asset utilization and improved drivers' efficiency. For example, if trip times are reduced, a truck would be able to make a larger number of trips or pick-ups and deliveries per day or a smaller fleet would be needed for the same volume of shipments; therefore, the cost per trip or pick-up and delivery would drop.

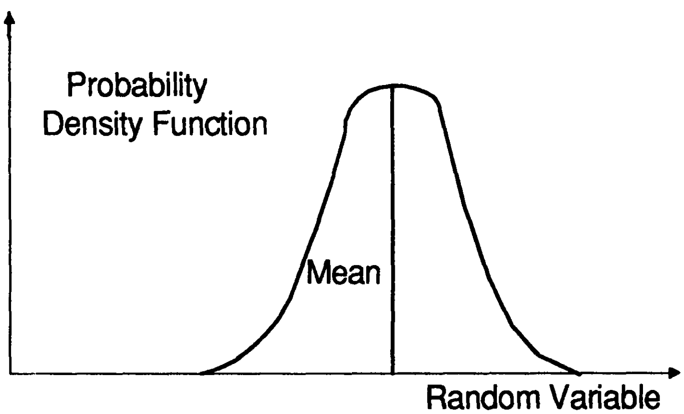
A component of the shippers logistics costs is in-transit inventory cost which is the cost of having the merchandise on-board vehicles during the trip time. Therefore, a reduction in trip time results in a decrease in the shippers logistics costs. Although the reduction in trip times due to dynamic routing may not seem large enough to significantly affect shippers logistics costs, such reductions are considerable for perishable goods.

Also a reduction in trip time would allow the carrier to carry out faster pickups in addition to faster deliveries. Faster deliveries and pickups would result in a more attractive service to shippers.

3.2.2 Trip Time Reliability



a) Probability distribution of a random variable with a large variance.



b) Probability Distribution of a random variable with low variance.

Figure 3.2.2.1

The trip time of shipments between two nodes can be presented as a random variable which has a certain probability distribution. Trip time reliability is a measure of the variance of trip times which is the concentration of trip times around the mean. Trip time reliability is improved by increasing the concentration of trip times around the mean (i.e. decreasing the variance). Figures 3.2.2.1 "a" shows the probability distribution of a random variable with a large variance. Figure 3.2.2.1 "b" shows the probability distribution of a random variable with a small variance.

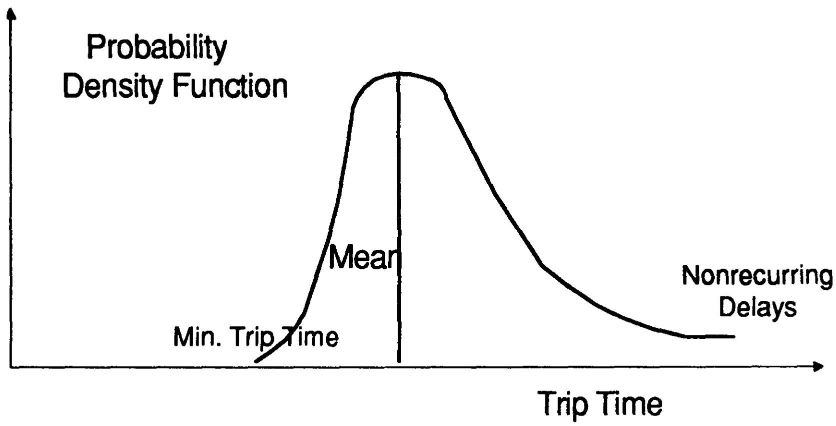


Figure 3.2.2.2

Probability distribution of trip times between two fixed nodes

Figure 3.2.2.2 shows an example of the probability distribution of trip times between two nodes using one route. The minimum trip time is that where the vehicle is traveling at the maximum allowable speed (e.g. highway speed limit). The trip times that are considerably larger than the mean are due to nonreccuring delays. The occurrence of such delays has a significant effect on the trip time reliability. Dynamic fleet management improves trip time reliability by allowing fleet controllers to react effectively to nonrecurring incidents that cause delays.

The nonrecuring long delays are, often, caused by unexpected traffic blocks. In an AVL and dynamic fleet management system, vehicle routes are updated based on real-time information on traffic conditions and vehicle positions. Therefore, unexpected delays caused by traffic blocks can be avoided.

Furthermore, vehicles can breakdown, be involved in an accident, or get stuck in a storm. In such cases, deliveries of on-board shipments are significantly delayed resulting in poor trip time reliability. In a dynamic fleet management system, information about vehicle positions and loads (e.g. number, size, and destination of shipments on-board each vehicle) are integrated, and the appropriate vehicle can be dispatched to provide assistance or finish the deliveries of the disabled vehicle at optimal costs and minimum delay. Therefore, the AVL and dynamic fleet management would reduce the carriers costs and delays in case of an emergency.

High trip time reliability would allow for the reduction of safety stock at the shippers receiving end, therefore lower logistics costs. In some cases, factory inventory can be totally eliminated, and this is referred to as "Just-in-Time" delivery (JIT) where trucks serve as mobile warehouses. When a JIT shipment reaches a factory, it is unloaded directly onto the assembly line. Therefore, high trip time reliability is crucial for the manufacturer who needs to schedule his manufacturing operations. Furthermore, high trip time reliability improves reliability of pick-ups which makes the service a more attractive one.

3.2.3 Capacity Management

Fleet managers try to maximize the capacity utilization of vehicles by properly scheduling and assigning shipments to vehicles. Capacity of freight vehicles is not fully exploited and there is a potential of increasing capacity utilization by dynamically managing fleets using an AVL system. Planning of operations has traditionally been based on static schedules to serve given demands. This section describes the static scheduling method. Then, it introduces dynamic scheduling using an AVL and dynamic fleet management system and shows its potential benefits in capacity management.

Demand for shipments can be fixed or deterministic. For example, newspapers need to be distributed every morning from the publishing center to fixed known locations. In such cases, the carrier can pre-plan an optimal tour or sequencing of stops for each vehicle. On the other hand, in many cases, demand for shipments between random geographic locations arrive at random times.

The traditional method for planning a service for random demands is to divide the operating hours into intervals (referred to as planning intervals), group the demands that arrive in each planning interval into a batch, and serve each batch in the upcoming interval. In this method tours of vehicles can be pre-planned in the same fashion as in the deterministic case. The length of the planning intervals depends on the size of the operating area, type of service offered (parcel, LTL, or TL), and speed of service offered by the carrier. As the length of the planning interval is reduced, the speed of the service is increased.

However, decreasing the length of the planning interval results in lower capacity utilization of vehicles and lower productivity of drivers. Assuming a constant rate of demand, as the length of the planning interval decreases, the portion of the demand captured by each interval decreases. Pre-planning for a smaller portion of demand in each planning interval results in lower capacity utilization of vehicle and productivity of drivers.

In an AVL and dynamic fleet management system,, real-time information about customers' demands, vehicle positions, and vehicle load status (number, size, and destination of on-board shipments) are integrated top update the vehicles' tours or schedules. The tours are updated to improve capacity utilization of vehicles and divers' productivity while satisfying the time constraint of the speed of service offered.

A policy can be developed to determine if a new demand should be included in the current tours of the operating vehicles (i.e. by dynamically updating the current tours) or in the static plan of the upcoming interval.

For example, a reasonable policy would be to dynamically update the tours of the operating vehicles to serve a demand if the marginal cost of this service is less than the average cost of serving a similar demand, else the demand should be scheduled in the upcoming planning interval.

Therefore, AVL and dynamic fleet management systems are expected to improve capacity utilization of vehicles and productivity of drivers. Such improvements will be more substantial when quick response service is offered.

For shippers, quick response services are becoming more important. Retailers have started to implement the Just-in-Time delivery system. Retailers have discovered that JIT deliveries could lower their inventory, provide fresher food and consumer responsive products with high turn-over. Therefore, JIT systems are expected to increase sales and reduce costs of retailers especially for goods that are perishable. When JIT is applied, schedules can no longer be set-up by the carrier, and the retailer needs to schedule his deliveries based on his needs.

For example, if a delivery was defective or if the demand was greater than expected, the retailer would be short of the product and would loose sales and damage customer loyalty. In such cases, the retailer would need quick response deliveries[14].

Finally, if information about the destination of parcels or LTL shipments on-board vehicles is provided , then knowing the vehicles' locations might enable the carrier to carry out vehicle to vehicle movement of LTL shipments. For example, exchanging shipments between vehicles might aim to load each vehicle with shipments going to the same area of destination. In essence, this is a sorting process typically carried out at hubs or terminals.

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[14] Fujita, Takako, "Challenges in Implementing the Just-In-Time System in the US Retail Industry", MIT Sloan Thesis, MS Management, May 1992, pp24.

Therefore, an AVL system might enable LTL carriers that operate consolidation hubs to significantly reduce the capacity of their hubs.

3.3 Summary of Benefits of AVL and Dynamic Fleet Management

This section is a summary of the benefits of AVL and dynamic fleet management to commercial carriers. Automatic Vehicle Location (AVL) systems provide real-time information about vehicles' locations. A central system can be used to integrate location information with other real-time information such as traffic and weather information. The central system can then update the vehicles' operating plans dynamically to improve service and reduce costs.

AVL would enable carriers to provide customers with instant shipment tracking information and real-time updates on shipment arrival times. It would, also, help deter hi-jacking and theft of vehicles and enhance emergency response in case of accidents. AVL would enable carriers to accurately monitor and control drivers' performance in real-time. The information from AVL systems can be saved in data files, and the productivity of different drivers can then be compared. Finally, the arrival times of vehicles at terminals can be updated when AVL is used. Such information can be used to improve space and asset utilization of terminals.

Furthermore, vehicle positions from AVL systems can be integrated with real-time information about traffic, weather and customer demand to improve level of service and reduce costs.

Traditionally, routing of vehicles is pre-planned by assuming constant travel times between nodes. However, traffic flows and travel times are affected by countless factors that are, in many cases, random. In such cases, the travel time estimates no longer apply, and the static operating plans results in long trip times and poor trip time reliability. Dynamic routing based on real-time traffic and weather information will reduce trip times and improve trip time reliability. Also, vehicles can breakdown, be involved in an accident, or get stuck in a storm. In a dynamic fleet management system, the appropriate vehicle can be dispatched to provide assistance or finish the deliveries of the disabled vehicle at optimal costs and minimum delay. This would improve the trip time reliability of service at optimal cost.

Demand for shipments is often random in terms of geographic locations and arrival times. In an AVL and dynamic dispatching system, the fleet operator can effectively manage the capacity of the fleet in real-time on basis of customers' needs. This would improve vehicle capacity utilization especially for quick response services. Furthermore, if information about the destination of parcels or LTL shipments on-board vehicles is provided , then knowing the vehicles' locations might enable the carrier to carry out vehicle to vehicle movement shipments. This would enable carriers to reduce the capacity of their sorting centers. Finally, changes in the shippers' plans can be accommodated efficiently using an AVL and dynamic fleet management system.

4 Application of AVL and Dynamic Fleet Management Systems

As described in Chapter 2, an AVL and dynamic fleet management system is an assembly of AVL, communication, and information subsystems. Alternative technologies, varying in costs and capabilities, are available for use in each subsystem. A carrier considering the use of an AVL and dynamic fleet management system typically seeks to identify the best combination of technologies. This chapter proposes a method that can be used by carriers to select the technologies for AVL and dynamic fleet management systems. The chapter also presents a case study of a hypothetical carrier, EXPRESS ONE, as an example to demonstrate how the method can be used and how the research conducted for this thesis can be used in real world applications.

First, a description of the method is provided. Second, the case study is presented and discussed.

4.1 Method Description

This section proposes a method that helps carriers select the technologies for AVL and dynamic fleet management systems. The method is based on a cost/benefit analysis. Therefore, the choice of a combination of technologies depends on the cost and benefit of that combination.

As illustrated in chapter 3, the magnitude and dollar value of the benefits of AVL and dynamic fleet management systems depend on the operating environment (i.e. fleet size, size of operating area, urban/intercity etc.), type and quality of service offered, and the capabilities of the technologies used (i.e. position fixing accuracy of AVL, accuracy of information technology in calculating shortest routes, coverage of communication system etc.). It is assumed that for a given carrier the operating environment and the type and quality of service offered are given, and the choices of technology are to be determined.

Therefore, for a given carrier, both the costs and benefits of an AVL and dynamic fleet management system are a function of the selected technologies. Also, the cost of a system depends on the selected technologies.

Ideally, the system (i.e. the combination of technologies), that results in the maximum positive net benefit (i.e. the difference between benefits and costs) to the carrier while satisfying any given constraints, is the best option. The primary constraints are that the selected technologies are required to fulfill the roles of the subsystems and to be compatible (ref. section 2.4 Integration of Technologies). Other limitations such as budget, implementation time frame and capacity requirements may be additional constraints.

The cost of an AVL and dynamic fleet management system can be easily determined using the costs given in Appendices A and B.

The benefits of an AVL and dynamic fleet management system are cost reductions (i.e. improvements in efficiency of labor and utilization of assets) and/or service improvements (i.e. faster, more reliable service etc.). For a certain AVL and dynamic fleet management system (i.e. for a certain combination of technologies), the magnitude such benefits can be estimated by modeling the fleet's operating system and simulating its operations assuming that the given AVL and dynamic fleet management system is applied.

The magnitude of cost reductions can be easily transformed to a dollar value. The more complex task is to estimate the dollar value of the service improvements. For example, if the expected improvement in trip time reliability is 25% when system "A" is used and 20% when system "B" is used ("A" and "B" are two hypothetical AVL and dynamic fleet management systems that use different combinations of technologies), it is very complicated and sometimes impossible to estimate how much more money would the shippers be willing to spend for the additional 5% that system "A" provides.

Therefore, estimating the net benefits, that include the value of service improvements, of AVL and dynamic fleet management systems is not always achievable. This section proposes a more conservative but feasible strategy for choosing the appropriate combination of technologies for a carrier.

The proposed strategy considers the cost reductions as the primary benefits of using an AVL and dynamic fleet management system. Therefore, the net benefit of using a certain system is assumed to be the difference between the resulting cost reduction and the cost of the system. Since the net benefit does not account for service improvements, all systems that satisfy the given constraints and result in positive net benefits are considered for further investigation. The final choice is then made based on the type and level of service of service the carrier is offering.

If the carrier is serving a market where the quality or level of service is important for the shipper, then the system that results in the maximum improvement in the quality of service is chosen. If the carrier is serving a market where the quality of service is unimportant (e.g. transportation of coal), then the system that results in the maximum net benefit (i.e. max.[cost reductions - cost]) is chosen.

Also, in selecting its technologies for an AVL and dynamic fleet management system, the carrier should consider future potential benefits that might not be attainable at the time of installation. For example, dynamic routing of vehicles in some urban areas might not be attainable because of the lack of real-time traffic information. However, in such cases, the carrier, installing an AVL and dynamic fleet management system, should consider the likelihood of the availability of real-time traffic information in the future and the resulting potential trip time reductions.

This strategy might not result in the optimal choice of a system or combination of technologies. However, it is a conservative and safe solution considering the uncertainty in the dollar value of service improvements. The following section presents a hypothetical example of the use of the proposed method by a carrier considering the installation of an AVL and dynamic fleet management system.

4.2 Hypothetical Case Study

4.2.1 Introduction

The purpose of this case study is to present the usefulness of the proposed method in assisting commercial carriers select the AVL and dynamic fleet management system suited for their application. It, also, aims to demonstrate how the research conducted for this thesis can be used in real world applications. The case study is a hypothetical one which considers a non-existing motor carrier interested in implementing AVL and dynamic fleet management to enhance its operations.

This section will consist of seven subsections. The first subsection is the introduction. The second subsection will describe the commercial carrier under consideration, present its capabilities, limitations and operational procedures, and discuss why the carrier is considering the implementation of an AVL and dynamic fleet management system. The third subsection will discuss the project limitations put forth by the carrier in terms of the available budget, resources and other considerations. The fourth subsection will study the operating environment of the carrier's fleet and how it may affect the choice of technologies. The fifth subsection will discuss the variables that differentiate the alternative technology options for AVL and dynamic fleet management system. The sixth subsection will summarize the applicable choices with a discussion that will lead to a final recommendation regarding alternatives or implementation scenarios for the project. The seventh subsection will present the conclusion.

4.2.2 Description of the Commercial Carrier

This section will describe the commercial carrier under consideration, EXPRESS ONE, along with its capabilities, operational procedures, limitations and a discussion on why it is considering the implementation of an AVL and dynamic fleet management system. EXPRESS ONE is a letter and package delivery service carrier which operates in New England.

EXPRESS ONE operates its own trucks and pick-up and delivery (pud) vans to pickup and deliver letters and packages within New England. It, also, operates seven consolidation and sorting centers or hubs (of varying sizes and capacities) strategically located in the six New England states from Connecticut to Maine.

Letters and packages get collected (using the pud vans) at the nearest hub and get sorted out based on the destination hubs. The letters and packages then get transported to the destination hub using trucks. At the destination hub, the letters and packages are sorted for delivery. Finally, the letters and packages get distributed from the destination hub using pud vans.

Originally, EXPRESS ONE focused on large volume shippers who had a pud van call on them daily for pick-ups and deliveries. Ordinary shippers without a daily service call had to call in advance to arrange for a pick-up. If a request for a pick-up was received before noon, the pick-up was served in the afternoon. Consolidated shipments were moved between hubs over night. The letters and packages were delivered before noon of the business day following the pick-up.

Such a service allowed EXPRESS ONE to pre-plan and maximize the utilization and efficiency of the pick-up and delivery vans and drivers, respectively. EXPRESS ONE's highest rated costs is its pick-up and delivery vans and drivers. On average, each pud van serviced around 120 demands per day.

However, EXPRESS ONE started losing market share to the more established and larger package delivery companies that offered the same service at lower prices. Such companies enjoyed cost savings from economies of scale that EXPRESS ONE was not able to match.

A recent study that was conducted by a consultant hired by EXPRESS ONE showed that the efficiency of operations and/or quality of service can be significantly improved if an AVL and dynamic fleet management system is implemented. The main purpose of the AVL and dynamic fleet management system would be to help EXPRESS ONE manage its' pud vans and sorting and consolidation hubs.

Real-time information about demands for pick-ups, pud van positions (from AVL), and their on-board shipments can be integrated to update the tours of the pud vans (i.e. their sequencing of stops). The tours are updated to improve the utilization and efficiency of the vans and drivers, respectively, while satisfying the constraints of the service offered.

Also, if positions of vehicles (both trucks and pud vans) heading to the hubs is known in real-time (by using AVL), their arrival time at the hub can be continuously updated. Up-to-date information about shipment arrival times can be used to improve labor, equipment and space management at the hub.

The consultants report concludes that the implementation of an AVL and dynamic fleet management system will result in considerable cost savings in the hub operations. It also concludes that the cost of pick-up and delivery operations can be significantly reduced while keeping the same service or a faster pick-up service can be offered at the same cost (e.g. offering pick-up within half an hour after a request is placed).

Finally, the report adds that additional benefits can be gained from implementation of an AVL and dynamic fleet management system. A customer information system that offers real-time shipment status information can be setup. Dynamic routing of vehicles based on real-time traffic and weather information can be carried out to reduce trip times and improve trip time reliability. Safety and security of vehicles can be increased. Drivers' performance can be monitored accurately and efficiently in real-time.

Also, vehicle or shipment positions can be saved in data files. The arrival and departure times of vehicles to and from the terminals can be automatically recorded by AVL. Such information is typically registered manually. Manual archiving is slow and inaccurate. AVL would carry such a task with greater efficiency and accuracy. This is expected to reduce the time vehicles spend at terminals, reduce errors which, for example, might lead to sending shipments to wrong destinations, and eliminate the need for attendants that carry out the exit and entrance paperwork.

4.2.3 Project Limitations

There are several limitations (put forth by EXPRESS ONE) that affect the implementation of the AVL and dynamic fleet management project. The limitations include budget issues, implementation time frame and system maintenance issues. This section will briefly discuss those issues and map the respective project requirements.

4.2.3.1 Budget

The budget allocated for the AVL project is a key element affecting the choice of the system. Although the allocated budget is somewhat flexible, the board of directors of

EXPRESS ONE insisted on maintaining a very low budget for this project. The total allocated budget for the AVL and dynamic fleet management project is set to be $2 million.

4.2.3.2 Implementation Time frame

The implementation time frame is also important in regards to the choice of an implementation scenario and system. EXPRESS ONE would like to install and start operating the system within the next 12 to 18 months. EXPRESS ONE is beginning to get affected by the aggressive competition and needs to lower its service prices and/or improve its quality of service.

4.2.3.3 Maintenance

Another consideration that EXPRESS ONE is very careful about relates to the level of maintenance that new systems require. EXPRESS ONE maintains a business philosophy which favors low maintenance equipment.

4.2.4 Operating Environment

The choice of technology for AVL and dynamic fleet management systems, partly, depends on the operating environment of the carrier's fleet The aim of this section is to study the elements of the operating environment that affect the choice of technology.

The studied elements are the size of the operating area, fleet size, arrival rate of pick-up demands, mean distance between adjacent roads, and frequency of unexpected traffic delays.

EXPRESS ONE's fleet is divided into pick-up and delivery (pud) vans that operate, mainly, in urban areas, and trucks, that operate between hubs (i.e. mainly, intercity).

4.2.4.1 Size of the Operating Area

The choice of technology is limited to the technologies whose geographic coverage capability includes the operating areas of EXPRESS ONE's fleet. The operating area of EXPRESS ONE's trucks, that move consolidated the shipments between hubs, is the entire New England area. The operating area of the pud vans is limited to the urban areas served by each hub.

4.2.4.2 Fleet Size

The required capacities of the selected AVL, communication and information technologies are partly dependent on the fleet size. As the fleet size increases, larger capacities are required. EXPRESS ONE operates 600 pud vans (around 70 to 90 per hub) and 50 trucks.

4.2.4.3 Arrival Rate of Pick-up Demands

This is the arrival rate of pick-up demands, that are received by each hub.

EXPRESS ONE is planning to use the AVL and dynamic fleet management system to update vehicles' tours based on real-time information about customers' demand and vehicle positions. Therefore, the number of vehicle positions to be determined and sent to the control center per interval of time (i.e. polling rate) is determined by the arrival rate of pick-up demands. As a result, the capacity of the selected communication and AVL technologies depends on the arrival rate of pick-up demands. As the arrival rate of pick-up demands increases, the selected AVL and communication technologies are required to have larger capacities.

The vehicle tours are updated by the information technology whenever a new demand arrives. Therefore, as the arrival rate of pick-up demands increases, the selected information technology is, also, required to have a larger capacity. On average, EXPRESS ONE receives around 400 pick-up demands per hour per hub.

4.2.4.4 Mean Distance between Adjacent Roads

This is a measure of the proximity of the roads that are used by the operating vehicles.

When AVL and dynamic fleet management systems are used to dynamically route vehicles based on real-time information about vehicle positions and traffic information, the mean distance between adjacent roads is the key factor that determines the required position fixing accuracy of the selected AVL technology.

When the mean distance between adjacent roads is high (e.g. 10 km), the effectiveness of the use of an AVL technology with high position fixing accuracy (e.g. position fixing error of 10 meters) in dynamic routing would be similar to one with low position fixing accuracy (e.g. position fixing error of 500 meters). However, when the mean distance between adjacent roads is low (e.g. 100 meters), the effectiveness of the use of an AVL technology with high position fixing accuracy in dynamic routing becomes significantly higher than one with low position fixing accuracy. Therefore, the use of AVL technologies with high position fixing accuracy is more attractive in urban areas.

Even though EXPRESS ONE is not currently planning to use the system for dynamic routing of vehicles, the possibility of such an application in the future should be considered in selecting the technologies.

EXPRESS ONE's trucks operate on intercity highways where the mean distance between adjacent roads is high (around 3 km on average). The pud vans operate in urban areas where the mean distance between adjacent roads is low (around 40 meters on average).

4.2.4.5 Frequency of Unexpected Traffic Delays

If EXPRESS ONE decides to use the AVL and dynamic fleet management system to dynamically route vehicles based on real-time information about vehicle positions and traffic information, then the number of vehicle positions to be determined and sent to the control center per interval of time (i.e. polling rate) would depend on the frequency of unexpected traffic delays. Therefore, the capacity of the selected communication and AVL technologies would depend on the frequency of unexpected delays. As the frequency of unexpected delays increases, the selected AVL and communication technologies are required to have larger capacities.

Also, the routes of vehicles are updated by the information technology whenever an unexpected traffic delay occur. Therefore, as the frequency of unexpected traffic delays increases, the selected information technology is required to have a larger capacity.

4.2.5 Technology Variables

Alternative technologies are available for use in the AVL, communication and information subsystems of an AVL and dynamic fleet management system.

This section will summarize some of the key variables that differentiate the technology options. Since these variables are discussed in more detail in Appendices A and B and in Chapter 2, this section will simply list the variables along with a brief description on their significance.

The key variables that differentiate the technology options in regards to commercial vehicle applications include:

4.2.5.1 Cost

This includes capital and operating and maintenance costs. Capital cost is a key variable that differentiate the different technologies that can be used for commercial vehicle applications. Capital cost varies depending on the level of sophistication of the technology. Capital cost is also affected by economies of scale especially for computer information technology.

Operating costs that are associated with the technology options for an AVL and dynamic fleet management systems involve power usage and subscription fees that would be charged by the providers of services. This is typically significant when communication systems such as cellular or mobile satellite technology is used. Operating costs might also include the cost of the employees (e.g. for manual information systems). Depending on the level of sophistication of the system and the technology that is employed, the operating costs could be considered as a variable that differentiates one technology from the other.

Maintenance costs depend on several factors including the availability of the maintenance expertise - in-house maintenance experts or contractors - and the specific technology employed. In addition, the frequency of required maintenance may affect the maintenance cost.

4.2.5.2 Geographic Coverage Capability

The geographic coverage capability of technologies for an AVL and dynamic fleet management system is key to the application. Some technologies operate worldwide, some cover North America or other parts of the world, where others cover local regions such as the Northeast region. Depending on the application, having extended coverage might not be useful functionally and would only increase the capital and operating costs.

4.2.5.3 Accuracy

The position fixing accuracy is another key element that differentiate the AVL technologies only. The accuracy of a system should reflect the functional requirements, and added accuracy should be carefully weighed against the additional capital cost.

4.2.5.4 Capacity

The capacity of an AVL technology is the maximum number of vehicle positions that can be determined per interval of time. The capacity of a communication technology is the maximum number of users of the system at any one time. The capacity of an information technology is the maximum number of vehicles that can be monitored and dynamically managed by the information system per interval of time. The capacity of a technology is also a key factor the decision process.

4.2.5.5 Reliability

Reliability is generally measured in terms of mean time between failures. Reliability of a technology is generally considered a key factor in determining the technology's acceptance by the client.

There are several commercially available AVL systems that a company such as EXPRESS ONE can choose from. Table 1 and Table 2 in Chapter 2 compares the characteristics and costs of the different available AVL and communication technologies.

4.2.6 Decision Analysis

This section presents the decision analysis for selecting the technologies for EXPRESS ONE's AVL and dynamic fleet management system. The decision analysis considers all the technology options studied in Chapter 2 and follows the method described in section 4.1.

An AVL and dynamic fleet management system is an assembly of AVL, communication, and information subsystems. Table 3 lists the available AVL, communication and information technologies. More than one technology can be used in each subsystem. The costs, capabilities and characteristics of the following technologies can be found in Chapter 2 and Appendices A and B.

Table 3

Technology Options

AVL Technologies	Communication Technologies	Information Technologies
Address Reporting (voice or electronic)	Hard-Line Telephone (electronic or voice)	Manual
Identification (ID) Systems	Paging Systems (electronic or voice)	Computer
Dead Reckoning	Two-Way Radio (Public or Private network), (electronic or voice)	
Direction Finding (Public or Private network)	Radio Cellular Telephone (electronic or voice)	
Hyperbolic Radio Navigation Systems	Mobile Satellite System (electronic or voice)	
a) Decca (Public or Private network)		
b) Loran-C (Public or Private network)		
c) Radio Cellular (analog and digital)		
Global Positioning System		

Section 4.2.6.1 presents the constraints limiting the selection of technologies. Section 4.2.6.2 discusses the cost effectiveness (i.e. cost reductions are compared to the costs) of

the combination of technologies that satisfy the given constraints. In section 4.2.6.3, the systems (i.e. combination of technologies), that satisfy the given constraints and are cost effective (i.e. cost reductions > costs), are compared, and the final choice is made.

4.2.6.1 Constraints on Technology Choice

The aim of this section is to present the constraints on the choice of technologies for EXPRESS ONE's AVL and dynamic fleet management system. The constraints include the compatibility and adequacy of the selected technologies (ref. section 2.4), project limitations put forth by EXPRESS ONE (ref. section 4.2.3), and operating environment constraints (ref. section 4.2.4). The technologies, that do not satisfy the presented constraints, are identified.

4.2.6.1.1 Compatibility and Adequacy of the Selected Technologies

The primary constraints are that the selected combination of technologies are required to be compatible and adequate to fulfill the role of the AVL and dynamic fleet management system (ref. section 2.4 Integration of Technologies).

Voice communication technologies can only be used for Address Reporting by voice, and manual information systems are compatible, only, with voice communication systems. Also, hard-line telephone systems can be used, only, with identification systems with roadside "readers" and Address Reporting by public phones.

To fulfill the role of the communication subsystem, paging and hard-line telephone technologies have to be used together (ref. section 2.4 Integration of Technologies). Finally, the selected AVL technologies are required to have a constant and predictable accuracy. Therefore, Dead Reckoning, Decca, and analog radio cellular (when used for

AVL) systems can be used, only, if positions are re-calibrated by Address Reporting or Identification systems (ref. sections 2.1.3, 2.1.5.1 and 2.1.5.3).

4.2.6.1.2 Project Limitations

The project constraints also include the project limitations which are put forth by the carrier. These project limitations were discussed in section 4.2.3 and include a limited budget ($2 million as capital cost), implementation time frame (between 12 and 18 months), and a maintenance policy that favors minimum maintenance.

Setting up a private infra-structure of roadside identification units for identification technologies and of radio towers for two-way radio communication, Loran, Decca and Direction Finding technologies, typically, requires more than 18 months. Furthermore, owning such private networks, that cover the New England area, requires a large capital investment, that, typically, exceeds the provided budget and requires significant maintenance (Appendicies A and B).

Therefore, the project limitations put forth by EXPRESS ONE excludes two-way radio communication, identification, Loran, Decca and Direction Finding technologies that use private infra-structure from the technology options.

The low maintenance policy of EXPRESS ONE also excludes the technology options with poor reliability. Direction Finders and Mechanical Dead Reckoning systems have poor reliability (ref. Table 1). Therefore, Direction Finding systems are excluded from the AVL technology options.

4.2.6.1.3 Operating Environment Constraints

The operating environment constraints include constraints on capacity and geographic coverage capabilities.

In EXPRESS ONE's AVL and dynamic fleet management system, it is assumed that each hub will have its own control center to monitor and manage its pick-up and delivery vans and inbound and outbound trucks (i.e. each hub will have an information system). EXPRESS ONE operates 50 trucks, 600 pud vans, and seven hubs. The number of pud vans varies from 70 to 90 vans per hub with each van servicing around 120 demands (pick-ups and deliveries) per day. Also, each hub receives around 400 pick-up demands per hour. Finally, an average of ten trucks visit each hub per day.

The selected technologies are required to have enough capacity to monitor and manage the 10 trucks and 90 pud vans with a demand arrival rate of 400 pick-up demands per hour (ref. sections 4.2.4.2 and 4.2.4.3). In such an environment, vehicles are polled (i.e. their position is determined and sent to the control center) once every few minutes. Therefore, the use of Address Reporting (voice and electronic), alone, is not suitable in such a case. As a result, Address Reporting, voice communication, public phones/pagers and manual information systems are excluded from the technology options. Furthermore, to attain the required capacity, AVL technologies have to carry both measurements and conversion of measurements to position coordinates on-board each vehicle.

Cellular service is only offered for communication and not for AVL in the New England area. Therefore, the cellular technology option for AVL is excluded. Also, the two-way radio public networks does not cover the entire New England area. Therefore, the two-way radio technology (using public networks) is, also, excluded from the communication technology options.

4.2.6.2 Cost Effectiveness

The combination of technologies that satisfy the constraints (discussed in section 4.2.6.1) are an assembly of a computer information system, radio cellular telephone or mobile satellite system for electronic communication, and any of the AVL technologies listed in Table 4. In all the AVL technologies in table 4, both measurements and conversion of measurements into position coordinates are carried on-board each vehicle.

Table 4

Remaining AVL Technologies

AVL Technologies
Inertial Dead Reckoning/Address Reporting
Hyperbolic Radio Navigation Systems
a) Decca (Public network)/ Address Reporting
b) Loran-C (Public network)
Global Positioning System

Mobile satellite systems provide continental coverage while the coverage of the radio cellular telephone systems is confined to the New England area. For a carrier such as EXPRESS ONE that operates in New England, mobile satellite systems do not have any advantage over radio cellular telephone systems. The cost of mobile sattelite systems is considerably higher than the cost of radio cellular telephone systems (ref. table 2). Therefore, for EXPRESS ONE, radio cellular telephone systems is used instead of mobile sattelite systems.

The total capital and operating costs of the considered systems (i.e. combination of technologies) are presented in Table 5. All the systems use radio cellular technology and computer technology for their communication and information subsystems, respectively. The selected AVL technology for each of the systems is specified in the second column of the table.

Table 5

Total Capital and Operating Costs of the Considered Systems

	Selected AVL Technology	Total Capital Cost ($)	Total Operating Cost ($ per day)
System # 1	Dead Reckoning/Address Reporting	1,150,000	900
	Hyperbolic Radio Navigation Systems		
System # 2	a) Decca/Address Reporting	860,000	900
System # 3	b) Loran-C	890,000	200
System # 4	GPS	1,350,000	200

In calculating the capital cost, it is assumed that each vehicle (vans and trucks) is equipped with an in-vehicle AVL unit (for measurements), in-vehicle interface unit (to take data from AVL unit to data terminal), in-vehicle data terminal (for electronic communication), and a radio cellular phone. The in-vehicle data terminal is assumed to have a software to convert measurements into position coordinates. Also, each of the seven hubs is assumed to have a computer information system that is also used for electronic communication.

The cost of the in-vehicle AVL units can be found in table 1. The costs of in-vehicle interface units and cellular phones can be found in Sub-Appendix B.5. The cost of the in-vehicle data terminal is assumed to be $100. The cost of the computer information system at the control center is assumed to be $25,000.

The operating costs include the subscription fees per cellular phone and per call. Subscription fees ($130 per year per phone) and fees per call can be found in Sub-Appendix B.5. It is assumed that positions are determined and sent to the control center every 5 minutes for the vans and every 10 minutes for the trucks. Whenever a vehicle position is sent to the control center, the communication link is used for 5 seconds. Vans and trucks operate ten hours each working day.

When Address Reporting is used for recaliberation, an additional cost of the time spent by the driver reporting his or her position. Address reporting is carried out every 30 minutes. It is assumed that the driver spends around 10 seconds whenever he or she reports an address. The cost of the driver is assumed to be $10 per hour.

The consultant report determined that EXPRESS ONE's pud van fleet can be reduced or a faster pick-up service can be offered with the same fleet. As described in section 4.1, the cost effectiveness of the systems is determined by considering the cost reductions only.

The report estimated a 10% reduction in the number of pud vans (if the speed of service is kept the same) and a 5% reduction in the costs of hub operations, when any of the considered systems is installed. The number of pud vans is 600, therefore, a 10% reduction is 60 vehicles and 60 drivers. Assuming that the cost of each van is $10,000 and that drivers are paid $10 per hour and work ten hours a day, the reduction in costs of pud vans is equivalent to $600,000 in capital cost and $6,000 per day in operating cost reductions. The 5% reduction in cost of hub operations was estimated to be around $2000 per day.

Therefore, all the considered systems that satisfied the constraints discussed in section 4.2.6.1 are cost effective, and their costs can be recovered after 2 to 4 months of operations.

4.2.6.3 Final Decision

The consultant's report determined, that if any of the considered systems was installed and EXPRESS ONE did not reduce its pud van fleet, a faster pick-up service can be offered. The service would offer pick-ups within half an hour after a request is placed. However, such a fast service is time sensitive, and reliability of pick-ups is expected to decline when this service is offered.

To maintain high reliability of pick-ups, real-time information about traffic and vehicle positions can be used to dynamically route operating pud vans. However, pud vans operate in urban areas where the mean distance between adjacent roads is small. As a result, an AVL and dynamic fleet management system can only be effective if an AVL technology with high position fixing accuracy is used (ref. 4.2.4.4).

System # 4 (ref. table 5) uses GPS as AVL technology. GPS has the highest position fixing accuracy, and, therefore, system # 4 would be the most effective in dynamic routing of pud vans.

EXPRESS ONE is serving a market where the quality of service is important. Therefore, out of the systems that satisfy the given constraints and that are cost effective, the system, that has the best potential for improving quality of service, is chosen. This makes system #4 (ref. table 5), which is a combination of GPS, radio cellular telephone and computer information technologies, the most suitable for EXPRESS ONE.

4.2.7 Conclusion of Case Study

This hypothetical case study have demonstrated the effectiveness of the method described in section 4.1, and discussed the factors affecting the choice of technology. It, also, showed how the research conducted in this thesis can be used for real world applications. It presented a typical case where AVL and dynamic fleet management can be used to help a carrier maintain its competitiveness by reducing costs and/or improving quality of service.

5 Conclusion

In an AVL and dynamic fleet management system, location information alone and when integrated with other real time information (e.g. traffic, weather, customers needs) is expected to improve asset utilization and efficiency of carriers and/or their level or quality of service. This thesis provides a study of the capabilities, characteristics and costs of the available technologies, that can be used in an AVL and dynamic fleet management system. It, also, provides a qualitative analysis of the benefits of such systems for a general case. The magnitude and value in dollars of these benefits have not been quantified. The application of AVL and dynamic fleet management systems to commercial transportation is, also, studied. A method that can be used by commercial carriers to select the appropriate technologies for their AVL and dynamic fleet management systems is proposed. A hypothetical case study is presented to demonstrate how this research can be used in real world applications.

The magnitude of the benefits depends on the operating environment and the characteristics and capabilities of the system used. For example, a system with high fixing accuracy would be more effective in dynamically routing vehicles in an urban setting compared to systems with lower fixing accuracy. Therefore, the percentage reduction in trip times is expected to be relatively high when systems with high fixing accuracy are used. The magnitude of benefits (both improvements in efficiency and asset utilization and in quality of service) can be estimated by modeling the fleet's operating system and simulating its operations assuming that the given AVL and dynamic fleet management system is applied.

The dollar value of benefits such as improvements in efficiency and asset utilization is the resulting cost reductions, which can be quantified. However, the dollar value of improvements in level or quality of service depends on how much shippers are willing to pay for such improvements.

For example, a coal shipper will not be prepared to pay for a reduction in trip time or improved trip time reliability; a coal shipper would typically go for the lowest price. Therefore, unless an AVL system increases asset utilization and operations efficiency enough to reduce costs and prices even after the investment for installing the AVL system has been made, the coal carrier would typically not consider installing an AVL system.

On the other hand, shippers of expensive goods are finding it costly to have their goods sitting on-board trucks and in warehouses especially if the commodity is perishable. Such shippers are typically willing to pay for high trip time reliability that will allow them to reduce their safety stocks.

For example, Bose Corporation, a sound systems manufacturer, operates a private fleet at a higher cost for the sole reason of maintaining high trip time reliability for their Just-In-Time (JIT) shipments. In manufacturing, JIT systems eliminate factory inventory and make trucks serve as mobile warehouses. The benefits of JIT systems are being realized by manufacturers and the application of the system is becoming more widespread. Saturn, the car manufacturer, maintains no inventory of car components although its suppliers are quite far locations, an average of 550 miles away from Saturn's factory. Also, Compaq, a leading PC manufacturer, have quintupled production without expanding office space partly because of JIT deliveries from component suppliers[15].

A method, that would help carriers select the appropriate technologies for their AVL and dynamic fleet management systems, has been proposed in section 5.1. This method is based on a cost/benefit analysis. Since it is very complex to quantify the dollar value of service improvements, the method considers the cost reductions as the primary benefits of using an AVL and dynamic fleet management system.

[15] Fortune Magazine Nov. 8, 1994.

Therefore, in the cost/benefit analysis, only, the cost reductions are compared to the cost of the system. All the systems whose cost reductions exceed their costs are considered for further investigation. The final choice is then made based on the type and level of service of service the carrier is offering.

If the carrier is serving a market where the quality or level of service is important for the shipper, then the system that results in the maximum improvement in the quality of service is chosen. If the carrier is serving a market where the quality of service is unimportant (e.g. transportation of coal), then the system that results in the maximum net benefit (i.e. max.[cost reductions - cost]) is chosen.

Although this method provides a conservative and safe solution (i.e. selection of technologies), it might not result in the optimal solution. The optimal selection of technologies can only be verified, if the dollar value of the improvements in quality of service is determined and included in the cost/benefit analysis. Therefore, further research on the estimation of the dollar value of improvements in the quality of service is recommended. This can be done by trying to estimate the shippers' willingness to pay more for a higher quality of service or the increase in market share due to the improvements in quality of service.

Appendix A

AVL Technologies

In an AVL system, the positioning process is divided into two parts. First, observations or measurements are taken. Second, the observations or measurement are converted into vehicle positions. Measurements can be taken on-board each vehicle or centrally. When measurements are taken on-board vehicles, converting the measurements into position coordinates can either be done centrally (typically at the control center) or on-board each vehicle. When measurements are taken centrally, conversions are done centrally.

Appendix A aims at describing, in more detail, the characteristics of the AVL technologies introduced in section 2.1. The basic principle, communication requirements, coverage, capacity, accuracy, reliability and costs of each system are discussed.

The basic principle describes the basic idea of the system. The communication requirements describe the communication system needed to send measurements or vehicle positions to the control center. The coverage is the area where vehicle positions can be determined. The capacity is the maximum number of vehicle positions that can be determined per interval of time. The accuracy is the error of the measured vehicle position with respect to the real vehicle position. The reliability of a system describes the rate of failure of the system.

AVL systems rely on communication technologies to send measurements or vehicle positions to the control center. Communication systems might have limited capabilities, for example, in coverage and capacity. Therefore, relying on a communication system might limit the capabilities of the AVL system in providing vehicle positions to the control center. Different types of communication technologies are introduced in the Communication Technologies chapter.

Finally, costs include both equipment and labor costs. Equipment costs include the capital, installation, maintenance, and operating costs. Approximate costs are provided for some of the systems.

A.1 Address Reporting

Basic Principle

Address Reporting is a positioning method that only uses communication and position calculation technologies. The basic principle is that a driver reports his or her address at a given time to the control center using a certain communication system. The vehicle's position is then determined at the control center.

Communication Requirements

A communication link is needed for the driver to report his or her address to the control center. The address can be sent by voice or by electronic messages. A mobile communication link is needed if the truck driver is frequently reporting his or her address, for example, whenever, a delivery or a pick-up has been made.

Coverage

Tne coverage of the system is the coverage of the communication system used.

Capacity

The capacity of the system depends on the time the communication link needs to be occupied for the message to be conveyed and is limited by the capacity of the communication link and the position calculation system used. As the time needed to convey the message increases, the positioning capacity (maximum number of reporting per interval of time) decreases because it is limited by the capacity of the communication link (maximum number of users at any one time). Reporting position by sending a complete address typically takes a longer time than reporting position by sending delivery or pick-up code or number. Reporting a position can either be carried out using voice messages or data messages that occupy the communication link for a smaller interval of time per message. In delivery cases, a package might have a bar code which can be read by a code reader and automatically send to the control center. Bar code reading is the fastest method for sending positions.

Accuracy

In general, accuracy depends on the accuracy of the driver in reporting position and the accuracy of the position calculation system at the control center. The most accurate address reporting would be reading bar codes of packages upon delivery. If the operating plans of the vehicles are pre-planned, then the control center can compare the positions of the reported address and the planned pick-up or delivery and is expected to detect any errors.

Reliability

The reliability of the system depends on the reliability of the position calculation system and the condition of the driver. For example, the driver might be feeling ill and might not be able to report his or her location.

Cost

The cost of completing the positioning process covers the cost of reporting and position calculation.

Table 5 shows the average times needed to report a location using different reporting schemes from an on-board communication system

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Table 5

Average Reporting Times

		Average Time for reporting (sec.)	Average Time to send messages (sec.)
Sending Complete Address	Voice	10	10
	Electronic Data	10	2
Sending Code for	Voice	5	5
Delivery or Pick-up	Electronic Data	5	1
Package Bar Code	Electronic Data	2	1

The average time for reporting is the time needed for the driver to make a reporting. The average time to send messages is the average time of using the communication system per reporting.

Reporting Costs

The cost of reporting an address includes the cost of the time spent by the drivers for reporting their addresses and the cost of any equipment and tags used for reporting.

1) Cost of the Driver

The cost of the time spent by the driver reporting his or her position would simply be the product of the rate ($ per interval of time) the driver is paid at and the average time needed to report a position (Table 5). The average time spent by drivers using different reporting methods is summarized in Table 1 and the average cost of a driver per hour is $20. The average time to report from a public phone is around 3 minutes.

2) Cost of Equipment

When Package Bar Code Reading is used as a reporting method, then the cost of reporting would include the cost of the bar code reader (around $200) and the cost of bar-code tag on each package (around $0.05).

Control Center Costs

This covers the cost of interpreting the messages of the drivers into locations. If the driver is reporting the address through voice communication then this cost would be the cost of the employee receiving the drivers message and finding the position on a map. The number of employees needed to receive address messages would depend on the rate of address reporting and desired capacity for position calculation. The estimated cost per employee is around $ 15.

If messages are sent electronically and the positions are determined using a computer system, then the control center's costs would be the cost of the software needed to interpret the address messages. It is assumed that the hardware used to receive the electronic messages can be used for position calculation. The cost of software is around $50.

A.2 Identification Systems

Basic Principle

Identification units are either readers or writers. A reader unit identifies a writer unit by reading the code of the latter. Codes can only be read when the reader is within a close range from the writer. Therefore, when a vehicle identifies a roadside unit or vice versa, the location of the vehicle can be estimated to be within a short distance from the roadside unit whose position is known. Therefore, the identification process is the measurement or observation that can be converted to position coordinates by using a computer system loaded with a data base that links the codes of roadside units to their positions.

Communication Requirement

To provide vehicle positions or identification information to the control center, an electronic communication link is needed between the reader and the control center. The communication system is required to automatically take information from identification units and send it to the control center.

If the in-vehicle unit is the reader , then a communication link from the vehicle to the control center is needed. If the position coordinates are determined at the control center, then this communication link is used to send the identification information. If the position coordinates are calculated on-board each vehicle, then the communication system would be used to send vehicle positions to the control center.

If the roadside unit is the reader then a communication link is needed between the roadside unit and the control center. Both ends of the link are fixed, therefore hardwire and/or radio systems would be suitable. This communication link is typically used to send identification information that is converted to vehicle positions at the control center. Hardwire links typically more capacity than radio links and are more reliable because the signal of radio links can be easily shielded especially in urban areas.

Coverage

The coverage of the system depends on the locations of the roadside units and the coverage of each roadside unit. The range or coverage of roadside units depends on their types. For example, microwave units have a relatively long range.

Capacity

The capacity of the positioning system depends primarily on the identification process (i.e. if vehicle is identifying roadside unit or vice versa). It also depends on the type of identification system used.

If the in-vehicle unit is the reader and the position coordinates are determined on-board the vehicle, then the capacity is unlimited. This is because the roadside unit can write to any number of vehicles within its range no matter what type of identification system used.

If the in-vehicle unit is the reader and the position coordinates are calculated at the control center, then the capacity of the system is limited by the capacity of the central position calculation systems used. The capacity of the system is not affected by the type of identification system used because the roadside unit can write to an unlimited number of vehicle units.

If the roadside unit is the reader, then the positioning capacity of the system depends on the type of identification system used and the number of roadside units installed. For example, the micro-wave reader can only read one unit at a time which is one vehicle at a time in this case. The positioning capacity is also limited by the capacity of the central position calculation system.

Accuracy

First, identification systems can only confirm that the position of a vehicle was within the range of a roadside unit at a given time. Therefore, the accuracy of positioning is limited by the range of the identification system used. Second, identification systems provides vehicle positions at discrete places. If the system is intended to be used for estimating vehicles' positions on a continuos time basis, then the accuracy of such a system would depend on the distance between roadside units and the strategic importance of their location.

Finally, position accuracy would depend on the accuracy of the system used to determine the position coordinates used.

Reliability

When identification systems fail to read a certain unit, position fixing cannot be carried out. Identification systems can only read units when the vehicle is traveling below a certain speed. The magnitude of this speed varies among different identification systems. For example, micro-wave systems can operate at a higher vehicle speed relative to low frequency radio identification systems. Snow, ice or dirt can lead to reading errors or in some extreme cases disable the identification system. Micro-wave systems typically have higher penetrability. Smart systems used to convert identification information into position coordinates might be able to correct some reading errors. If coordinates of positions are calculated at the control center, then such a system might have access to a larger data base that would allow for better correction capabilities relative to on-board systems.

Cost

The costs cover the cost of identification units and cost of the computer system that determines coordinates of positions. The cost of communication links that are needed are discussed in the Communication Technology chapter.

Costs of Identification Units

The identification process can be completed by having the vehicle unit identify roadside unit or vice versa. When vehicle units identify roadside units, the cost would be the cost of the in-vehicle "readers" and roadside "writers". Otherwise, the cost would be the cost of roadside "readers" and in-vehicle "writers".

Cost of Computer System

This covers the cost of the hardware and software needed to convert identification information into position coordinates. This can either be done using in-vehicle computer s or a central; computer system. A computer hardware can be used for a number of systems. Therefore, if computer hardware is already installed for other uses, then the following cost would be limited to the cost of the software.

A.3 Dead Reckoning

Basic Principle

In inertial systems, the gyroscope, which contains a certain mass, is installed on-board a vehicle and experiences the same acceleration as this vehicle. The accelerometer measures the force needed to accelerate the mass (contained in the gyroscope) with the same acceleration as the vehicle. Knowing the force needed to accelerate this mass, the acceleration can be determined. The time clock measures the time over which the acceleration remains at a steady state. Steady state of acceleration is constant linear, centripetal, and rotational accelerations. Knowing the initial angular and linear velocities at the beginning of the time interval and the length of the time interval, the measured acceleration is then integrated successively to determine the angular and linear displacements along the pre-defined axes. Given the initial position and the displacement of the vehicle, the new position at the end of the time interval can be determined.

The mechanical system measures the displacement of the vehicle using a number of devices. A compass is used to determine the bearing of the vehicle relative to the North, a level is used to measure the inclination of the slope, on which the vehicle is traveling, and a tachometer that measures the distance traveled by measuring the number of revolutions made by one of the vehicle's wheels over the time interval. The new position is updated whenever the vehicle changes its direction of travel. The new position is simply calculated by adding the displacement to the position of the vehicle at the beginning of the interval. Therefore, there is no need to measure the length of each time interval.

Communication Requirement

An electronic communication system is needed between vehicles and the control center. The communication system should be able to automatically send location information when measurements are converted into position coordinates on-board each vehicle or measurements when position coordinates are determined by a central system at the control center. Additional communication links may also be needed for correction systems such as Identification systems or Address Reporting system.

Coverage

In-vehicle Dead Reckoning units are self contained and do not rely on any external factors. Therefore, measurements can be taken anywhere.

The measurements can be converted to vehicle positions by using either an on-board or a central computer system. In addition to determining positions, the computer system can be used for correction by map-matching. The central system typically has a larger memory for storing data and maps; therefore, the area covered by a central map-matching system is typically larger than that covered by an on-board system.

Identification systems that might be used for correction will have limited coverage. Finally, the coverage of Address Reporting system that might be used for corrections is the coverage of the communication system used.

Capacity

When position coordinates are determined at a central system, the positioning capacity would be limited by the capacity of the central computer. Otherwise, if an on-board computer system is used to determine vehicle positions, then the capacity would only be unlimited.

Identification and Address Reporting systems would also have limited capacity if any is used for position corrections.

Accuracy

For the first position update where the initial conditions are accurate, the inaccuracy is mainly due to the inaccuracy of the measuring devices. The gyroscope, accelerometer, and time watch in inertial systems and the tachometer and compass in mechanical systems are expected to have certain degrees of inaccuracies. The use of the updated position and velocity of an interval as initial conditions for the next interval leads to the building up of error which might become time divergent. Automatic vehicle identification and address reporting systems can be used to correct updated positions to maintain an acceptable degree of accuracy. Recalibration every 20 miles results in an accuracy of 25 meters or better. Also map matching systems can be used for position correction. Central map matching systems typically have better correction capabilities compared to on-board systems.

Reliability

The reliability of the system depends on the reliability of the measuring devices, computers used to determine positions, and communication systems. Gyroscopes are typically highly reliable.

Cost

The costs of a Dead Reckoning system is the cost of the measuring devices and the cost of the computer systems that determine the position coordinates. In an inertial system, the measuring devices are the gyroscope, accelerometer, time watch. In a mechanical system, the measuring devices are a tachometer and a compass.

Cost of Computer Systems

This covers the cost of hard and software needed to convert measurements into position coordinates. Software is assumed to be capable to perform map matching corrections. The system can either be central or on-board each vehicle. A computer hardware can be used for a number of systems. Therefore, if computer hardware is already installed for other uses, then the following cost would be limited to the cost of the software.

Cost of Measuring Devices

This covers the cost of the gyroscope, accelerometer and time clock (total cost around $500) in case of an inertial system or the cost of the tachometer and compass (total cost around $300) in case of a mechanical system.

A.4 Direction Finding

Basic Principle

The alternating current in a transmitting aerial sets up lines of magnetic force, which are propagated at the velocity of light. If a changing number of magnetic lines of force pass through a surface enclosed by the windings of a coil, a voltage is induced in the windings. The Direction Finder uses a loop aerial with a number of windings in the circular tube which acts as a coil (Figure 2.1.4.1 in main text). The loop aerial can rotate about a vertical axis. The diameter of the loop depends on the wave length of radio signals.

When the loop aerial is located in the radiation field of a transmitter, magnetic lines of force pass through the windings. (Figure A.4.1). The number of lines alternately increases and decreases creating alternating voltage in the coil or loop aerial. When the plane of the loop is turned towards the transmitter, the maximum number of the lines of force would allowed to pass through the loop resulting in the greatest induced voltage. The voltage is zeroed when plane of loop is perpendicular to the direction of transmitter because no lines of force are allowed to pass through the loop. To determine the relative bearing of a transmitter with respect to a direction finder, the coil of the direction finder can be rotated to either the direction of maximum voltage where direction of transmitter would be the same as that of coil or to the position of zero voltage where the direction of transmitter would be orthogonal to the direction of the coil. In practice, to attain higher accuracy, the coil is always rotated to the position where no signal is heard (zero voltage) because, in this case, a small change in the position of the loop will then result in a rapidly increasing signal strength. On the other hand, a change in position away from the maximum would be harder to detect.

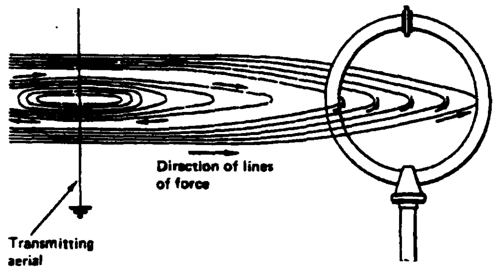

Figure A.4.1

Direction finder within a magnetic field[16]

If fixed stations with known positions are used for transmission, then a Direction Finder on-board each vehicle can determine its relative bearing with respect to the stations. Ideally, two bearing readings are enough for position fixing; however, to increase accuracy, three readings are typically carried out (Figure 2.1.4.3 in main text). The bearing readings are then entered into a software that determines the position's coordinates on a map.

Communication Requirement

A communication system is needed between vehicles and the control center to send location information in case measurements are converted into position coordinates on-board each vehicle or measurements in case position coordinates are determined by a central system at the control center. Therefore the communication system should be able to electronically transmit electronic data.

Coverage

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[16] Sonnenberg, G.J., "Radar and Electronic Navigation", 6th edition, Butterworths, 1988, pp94 Figure 3.2.

It is assumed that each vehicle is equipped with a Direction Finder and signal is transmitted from fixed transmission stations. Therefore, the coverage would primarily depend on the range or coverage of the fixed transmission stations.

Capacity

When the position coordinates of the vehicles are determined on-board each vehicle, the capacity of the system is unlimited. Otherwise, if position coordinates are determined at central system, the capacity would be limited by the capacity of the central position calculation systems.

Accuracy

Surrounding errors and night effects are the two main sources of error that affect the accuracy of the Direction Finder. Surrounding errors arise from the reflection of radio waves on surrounding surfaces causing the aerial to receive waves from several directions. Night effects causes the deviation of magnetic lines from horizontal although they remain perpendicular to the direction of propagation. This causes fading and therefore adjustment to minimum or zero sound becomes more difficult. Night effect is caused by the domination of sky wave reception at night especially at long ranges. During the day, the ionosphere is ionized more intensely by sunlight. The power loss of the waves from radio beacons is greater than at night. Therefore, during the day, only ground waves are receptible. Finally, the position fixing inaccuracy is the product of the bearing inaccuracy and the distance between the Direction Finder and the transmitter. Therefore, as the distance between the Direction Finder and the transmitters decreases, the position fixing error proportionally decreases. Map matching can be used for correction.

Reliability

The reliability of the system depends on the reliability of the Direction Finders, transmission stations, computer systems used to determine position coordinates, and communication systems used. Direction Finders are not highly reliable because a motor is used to rotate the aerial.

Cost

The cost includes the cost of the transmission stations, direction finders, and computer systems.

Cost of Transmission Stations

This covers the cost of land and transmission equipment. This cost can vary considerably depending on the station installed. Transmission stations have a high capital (anywhere from $10, 000 to 40,000) and maintenance cost.

Cost of Direction Finders

This covers the cost of Direction Finders (around $50 each). It is assumed that Direction Finders are installed on-board vehicles.

Cost of Computer Systems

This covers the cost of hard and software needed to convert measurements into position coordinates. The system can either be central or on-board each vehicle.

A.5 Hyperbolic Radio Navigation Systems

Basic Principle

The basic principle of hyperbolic systems is well described in the main text. Therefore, to avoid repetition of the same information, the reader is referred to section 2.1.5.

A.5.1 Decca System

Communication Requirement

A communication system is needed between vehicles and the control center to send location information in case measurements are converted into position coordinates on-board each vehicle or measurements in case position coordinates are determined by a central system at the control center. Therefore the communication system should be able to transmit electronic data.

Coverage

It is assumed that each vehicle is equipped with a Decca receiver and the signal is transmitted from fixed transmission stations. Therefore, the coverage would primarily depend on the range or coverage of the fixed transmission stations. There are long range public Decca chains operating in different places around the world including the north eastern part of the United States. Figure A.5.1.1 shows the coverage of the existing chains or under construction in 1986. Mini-chains can also be privately set up by transportation carriers.

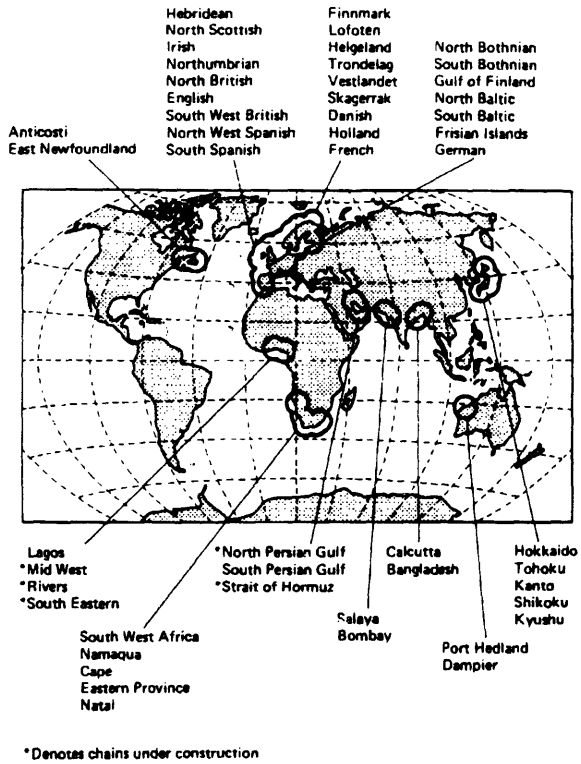

Figure A.5.1.1

Coverage of public Decca chains[17]

Capacity

When the position coordinates the vehicles are determined on-board each vehicle, the system would be a decentralized system whose capacity is unlimited . Otherwise, if position coordinates are determined centrally, the capacity would be limited by the capacity of the central system.

Accuracy

In Decca systems, the accuracy depends on the accuracy of measuring the phase difference between the signals from two transmitting stations and the rate of change of the line-of-

[17] Sonnenberg, G.J., "Radar and Electronic Navigation", 6th edition, Butterworths, 1988, pp133 Figure 4.7.

position (LOP) with respect to the measured phase difference. As the rate of change of line-of-position (LOP) with respect to the phase difference decreases, the fixing accuracy increases. Base lines are the segment that connect the master station and the slave stations. The rate of change of LOP with respect to phase difference is minimum at the base line and is maximum at the extension of the baseline.

Also, It is assumed that radio waves traveling between a transmitter and a receiver follow the line of great circle which is a straight line in short range systems. However, radio waves are typically reflected and the true paths becomes longer than the assumed straight line or line of great circle. This is a common inaccuracy among hyperbolic navigation systems which becomes more significant as the range of the system increases. Radio waves can be reflected, for example, by mountains or buildings in urban areas and by the ionosphere at night resulting in sky waves. Variable errors are caused by the simultaneous reception of ground and sky waves. Also, when waves travel over conductive terrain, their speed is expected to be distorted, therefore adding an additional source of inaccuracy. Snow and precipitation static affect the performance of the decometers.

Using a counter to count the complete revolutions of each decometer makes the positioning process a continuos one where errors typically build up with time. To overcome this problem, the position of the vehicle can be updated every interval of time.

The accuracy of positioning increases as the angle between the lines-of-position approaches 90 degrees. The larger the number of hyperbole drawn for a position fixing, it is more likely that two lines-of-position would intersect at right angles. In Decca systems, four stations are typically used to generate three hyperbolic lines-of-position. Corrections can be made for constant and predicted inaccuracies. For example, the effect of conductive terrain on fixing accuracy for a certain area can be assessed and corrections can be incorporated accordingly. On the other hand, sky wave errors are cannot be predicted in Decca systems.

A mini chain can be designed to provide maximum accuracy over the operating area of a transportation carrier. First, the operating area would be covered by ground wave signals. Second, the transmission stations would be situated in a way where most position fixes would be near a baseline and would be the intersection of hyperbolic lines-of-position intersecting at angles approaching 90 degrees.

Reliability

Reliability is dependent on the reliability of the transmitting stations, the on-board Decca receiver, and the computer system used to determine position coordinates.

Cost

The cost of a Decca system includes the cost of transmission stations in case of a mini private chain, the cost of Decca receivers, and the cost of computer systems that determines the lines-of-positions and locations of receivers.

Cost of Transmission Stations

This covers the cost of land and transmission equipment for a mini chain. One master and three slave stations are typically installed. This cost can vary considerably depending on the station installed. Transmission stations have a high capital (anywhere from $20, 000 to 70,000) and maintenance cost.

Cost of Decca Receivers

The covers the cost of Decca receivers (around $50 to 100 each). It is assumed that Decca Receivers are installed on-board vehicles.

Cost of Computer Systems

This covers the cost of hard and software needed to convert measurements into lines-of-positions and position coordinates. The system can either be central or on-board each vehicle.

A.5.2 Loran-C System

Communication Requirement

A communication system is needed between vehicles and the control center to send location information in case measurements are converted into position coordinates on-board each vehicle or measurements in case position coordinates are determined by a central system at the control center. Therefore the communication system should be able to transmit electronic data.

Coverage

The coverage of a Loran-C network is the geographical area covered by the network's chains of transmitting stations. The coverage of each chain depends on the locations and the range of transmitting stations used. If the signal of the master and the slave stations of a certain chain can be read at a certain point, then this point is considered within the coverage of the chain. However, a receiver can read and discriminate between sky and ground wave signals. The range of sky wave signals of a transmitting station is longer than the range of ground wave signals. Therefore, each transmitting station and consequently each chain would have a ground wave coverage area as well as a sky wave coverage area. The ground wave coverage area is included within the sky wave area which is larger.

Public Loran-C chains are in operation and almost cover the entire northern hemisphere. Because those chains were primarily built for marine navigation, transmission stations are situated on islands and along shorelines. Therefore, only coastal areas are covered by ground wave signals. A transportation carrier can install a private mini-chain to cover its operating area by ground wave signals.

Capacity

It is assumed that vehicles are equipped with receivers and the transmitting stations are fixed because, otherwise, a chain of fixed receivers would have limited capacity in reading the mobile transmitters. When the position coordinates are determined on-board each vehicle, the system would be a decentralized system whose capacity is unlimited . Otherwise, if position coordinates are determined at central system, the capacity would be limited by the capacity of the central system used to determine position coordinates.

Accuracy

In Loran systems, the accuracy depends on the accuracy of measuring the difference of arrival times (TD) of the signals from two transmitting stations and the rate of change of the line-of-position (LOP) with respect to the measured time difference (TD). Because of the use of pulse emission signals and the ability of the Loran-C receiver to perform simultaneous pulse and cycle matching, signal arrival time differences can be measured more accurately in Loran-C systems relative to Decca systems' measurements where errors build up with time. As the rate of change of line-of-position (LOP) with respect to time difference (TD) decreases, the fixing accuracy increases. The base line is the segment that connects the master station and one of the slave stations. The rate of change of LOP with respect to TD is minimum at the base line and is maximum at the extension of the baseline. Using the Loran-C signal provided by the Coast Guard, an average error of 25 meters is estimated near the base line and an error of 3 kilometers near the extension of the base line.

Also, it is assumed that radio waves traveling between a transmitter and a receiver follow the line of great circle which is a straight line in short range systems. However, radio waves are typically reflected and the true paths becomes longer than the assumed straight line or line of great circle. This is a common inaccuracy among hyperbolic navigation systems which becomes more significant as the range of the system increases. Radio waves can be reflected, for example, by mountains or buildings in urban areas and by the ionosphere at night resulting in sky waves. Loran receivers can discriminate between sky and ground wave; therefore, corrections for sky wave measurements can be incorporated. Areas covered by the sky wave signal, typically, have lower accuracy than those covered by ground signals. Also, when waves travel over conductive terrain, their speed is expected to be distorted, therefore adding an additional source of inaccuracy. Errors in areas of high conductivity can be assessed and corrections can be incorporated to improve accuracy. The Loran system signal provided by the Coast Guard has an average accuracy of (95%) 458 meters in ground wave reception areas.

The accuracy of positioning increases as the angle between the hyperbolic lines-of-position (that are branches of hyperbolae) approaches 90 degrees. The larger the number of hyperbole drawn for a position fixing, it is more likely that two of the lines-of-position would intersect at right angles. In Loran systems, one master and four slave stations are typically used to generate four hyperbolic lines-of-position. Unlike the Decca system, the positioning process is a closed loop where each position fixing is an independent process.

A mini chain can be designed to provide maximum accuracy the operating area of a transportation carrier. First, the operating area would be covered by ground wave signals. Second, the transmission stations would be situated in a way where most position fixes would be near a baseline. Finally, most position fixes would be the intersection of hyperbolae intersecting at angles approaching 90 degrees. Typical accuracy of a mini-chain is around 50 meters.

Reliability

Reliability is dependent on the reliability of the transmitting stations, the reliability of the on-board Loran-C receiver, cycle and pulse matching device, and the computer system used to convert measurements to position coordinates.

Cost

The cost of a Loran-C system includes the cost of transmission stations in case of a mini private chain, the cost of Loran-C receivers, and the cost of computer systems that determines the lines-of-positions and locations of receivers.

Cost of Transmission Stations

This covers the cost of land and transmission equipment for a mini chain. One master and four slave stations are typically installed. This cost can vary considerably depending on the station installed. Transmission stations have a high capital (anywhere from $60, 000 to 100,000) and maintenance cost.

Cost of Loran-C Receivers

The cost of a Loran-C receiver is around $100 including processor. It is assumed that Loran-C receivers are installed on-board vehicles.

Cost of Computer Systems

This covers the cost of hard and software needed to convert measurements into position coordinates. The system can either be central or on-board each vehicle.

A.5.3 Radio Cellular System

Communication Requirement

A communication system is needed between vehicles and the control center to send location information in case measurements are converted into position coordinates on-board each vehicle or measurements in case position coordinates are determined by a central system at the control center. Therefore the communication system should be able to transmit electronic data.

Coverage

The coverage of a cellular positing system is the range of the cellular network used. More can be found about cellular networks in section 2.2.5 in the Communication Technologies chapter.

Capacity

Assuming that signal arrival time difference measurement is carried out by each in-vehicle cellular positioning unit, the positioning capacity would be unlimited unless a central system is used to convert measurements into position coordinates. In this case, the positioning capacity of the system would be limited by the capacity of the central system.

Accuracy

In cellular systems, the accuracy depends on the accuracy of measuring the difference of arrival times (TD) of the signals from two transmitting stations. In analog systems, only the phase difference can be measured while the number of complete wave lengths are counted from a certain known starting point. Therefore, TD measurements in analog systems are dependent on previous measurements. This leads to the building up of errors that are expected to be time divergent. On the other hand, digital systems are closed loop systems where TD measurements are made independently by pulse and cycle matching. The accuracy also depends on the rate of change of the line-of-position (LOP) with respect to the measured time difference (TD). As the rate of change of line-of-position (LOP) with respect to time difference (TD) decreases, the fixing accuracy increases. In cellular systems, the base line is the segment that connects any pair of transmitting stations. The rate of change of LOP with respect to TD is minimum at the base line and is maximum at the extension of the baseline. In general, cellular systems are similar to mini chain hyperbolic systems.

Reliability

Reliability depends on the reliability of the cellular system used. Reliability also depends on the reliability of the in-vehicle cellular positioning unit that measures the signal arrival time difference and the computer system used to convert measurements to position coordinates

Cost

The cost includes the cost of the cost of in-vehicle cellular positioning unit that measures the signal arrival time deference (TD), the cost of the computer system that converts measurements into position coordinates and the cost of ten cellular service.

<u>Cost of Cellular Service</u>

This cost includes the subscription and annual maintenance fees that cellular phone companies charge in return for providing a radio cellular telephone service.

In-Vehicle Cellular Positioning Unit

This is the cost of the devices used to measure this difference in signal arrival time from two stations at a mobile phone (around $500 to 600). In case of a digital system, the device should be capable to carry out cycle and pulse matching. In case of an analog system, the device should be capable to measure phase differences (i.e. cycle matching) and should include a counter to count the number of complete wave lengths.

Cost of Computer Systems

This covers the cost of hardware and software needed to convert measurements into position coordinates. Software is assumed to be capable to perform map matching corrections. The system can either be central or on-board each vehicle.

A.6 Global Positioning System (GPS)

Basic Principle

The master station locates the satellites and informs each satellite which signal has to be transmitted to the users. The signal is a code describing the time of transmitting the signal according to universal time coordinates and the position of the satellite at that time. For simplicity, it is assumed that the receiver and the satellite are equipped with clocks which are synchronized. When the user receives the satellite signal, the time at which the signal was transmitted can be determined. By knowing the transmission and reception times of the signal, the travel time of the signal from the satellite to the receiver can be determined. Therefore, knowing that the travel path of the signal was a straight line, the distance between the satellite and the receiver is the product of the signal travel time and the speed of the radio signals which is around 300,000 km/sec.

Knowing that the receiver is at a constant distance from the satellite, it can be deduced that the receiver is at a point on a sphere whose center is the satellite and whose radius is the distance between the satellite and the receiver. When simultaneous readings from three different satellites are taken, the position of the receiver

would be one of the two points of intersection of the three spheres. Normally, these two points are far enough apart to avoid ambiguity. However, the clocks of the receiver/processor and the satellite are not always synchronized. Therefore, the clock's error which is the same for all readings can be taken as an additional unknown and determined by a fourth reading from a fourth satellite. The result would be the value of the clock error and the three dimensional coordinates of the receiver.

Further position fixing inaccuracies exist because of the refraction of radio waves in the ionosphere. The satellites are 20,200 km away from the earth; therefore, the path of a satellite's signal to all users within a certain area (around 100 km in diameter) will almost coincide and the radio waves will be subjected to the same refraction in the ionosphere. The principle of Differential GPS is that, for an area (diameter around 100 km), the position fixing error due to the refraction of waves transmitted by the satellites can be evaluated by obtaining a GPS position fixing for a point whose position is exactly known. Then assuming that the refraction error is constant within the chosen area, corrections can be applied for all the position fixing within that area.

Communication Requirement

GPS receivers typically have built in processors that converts the signals received from satellites into position coordinates. Therefore, a communication link is needed to automatically send real time location information from the mobile receivers to the transportation carrier's control center.

If DGPS corrections are broadcasted publicly (e.g. by FM radio waves) to GPS users then to receive DGPS corrections the GPS mobile units (i.e. receiver/processor) should include a receiver capable of receiving real time corrections in the form of electronic data. If a DGPS system is setup by the transportation carrier, then an electronic data link is needed to send corrections from control center to the vehicles.

Coverage

In 1990, there were 18 GPS satellites orbiting the earth along six circular orbits each with three satellites. The satellite configuration enabled users at any point on or near the surface of the earth to obtain their position by continuously receiving direct "line-of-sight" navigation signals from at least four satellites. Figure 2.1.6.1, in the main text, shows the 18 GPS satellites that were orbiting the earth by 1990. Since 1990, at least six additional GPS satellites have been launched.

The coverage of DGPS systems depends on the number and locations of the fixed GPS receivers/processors that are used to determine the refraction error. One fixed GPS unit is typically installed for an area whose diameter is around 100 km. Within each of such areas, the coverage depends on the range of the transmitting station that sends DGPS corrections to the users.

Capacity

GPS receivers typically have built in processors that converts the signals received from satellites into position coordinates. Therefore, the system is completely decentralized and has unlimited positioning capacity.

Accuracy

Having the satellites at high altitude of 20,200 km yields better accuracy because the satellite would be less affected by irregularities caused by unequal distribution of the mass in the earth. Older satellite positioning systems had their satellites at lower altitudes.

The error due inaccurate clock synchronization the GPS and the users is evaluated by reading an additional signal from a fourth satellite; therefore, the appropriate corrections can be incorporated. Typical GPS accuracy is around 10 meters.

Positioning errors due to refraction of waves is expected to be constant over an area with a diameter of around 100 km. For every area, a DGPS system can be used to measure the positioning error due to the refraction of waves; therefore, corrections can be incorporated. Typical DGPS accuracy is less than 5 meters.

Reliability

The reliability of a GPS system depends on the reliability of the GPS receiver/processor. While underground, in a tunnel for example, GPS receivers typically fail to receive the satellites' signals. In case of DGPS systems, the reliability of receiving corrections depends on the reliability of the computer system that determines the errors end corrections and the communication system used to carry the correction information to the mobile GPS receivers.

Cost

The cost of a GPS positioning system is simply the cost of the mobile receiver/processor and it ranges between $800 and a $1000 . If DGPS corrections are provided publicly, then the additional cost to receive DGPS corrections would be a receiver that can receive electronic data. If the DGPS system is set up by the transportation carrier, then its cost would be the cost of a fixed GPS receiver/processor that can determine the error due to refraction and the cost of a communication link that can transmit electronic data (i.e. corrections) to the mobile GPS receiver/processors. The costs of communication links is discussed in the communication technologies chapter.

Appendix B

Communication Technologies

Appendix B aims at describing the characteristics of the communication technologies introduced in section 2.2 in the main text. The coverage, availability of service, information transmission capability, mobility and cost of each system are discussed.

The coverage of a communication system is the area where the system is accessible and functional by the vehicle operator. For example, the coverage of a cellular phone system would be the area where a signal is provided.

The availability of service of a system is the users' average waiting time until the service is available. The availability of service typically depends on the capacity of the communication system which is the maximum number of users the system can serve at any one time. The availability of service also depends on the reliability of the system used. Reliability can be measured by the number of failures over an interval of time.

Information transmission capability of a system includes the type of messages that the system can convey (i.e. electronic or voice), the maximum lengths of messages that can be sent, and if such messages can be sent one way or two way through the system.

The mobility of a system is the ability to allow communication between the control center and the vehicle as the latter is moving.

The costs of a system includes both equipment costs and/or network fees. Equipment costs includes the capital, installation, maintenance, and operating costs.

B.1 Hard-Line Telephone

Hard-line telephone systems can be used to provide communication between drivers and the control center. It can also be used with identification systems to link roadside readers with the control center.

Coverage

The coverage of the hard line system depends on the coverage of the providing companies. Furthermore, even if an area is covered by the service of a telephone company, to be covered by the hard-line system, the dispatch center needs to be accessible from its telephone lines.

Availability of Service

When the system is used for communication between drivers and the control center, the availability of the service primarily depends on the distribution of public phones. For example, the distance between public phones along highways can be different.

In addition, once the driver is at a phone booth, the availability of service depends on the capacity of the system (i.e. the maximum number of users possible), the number of users at the time, and the quality of the telephone lines. In developing countries, these issues are often the cause of the unavailability of service due to the overloading of predated networks.

The system's capacity depends on the technologies deployed by the providing telephone companies. For example, networks with satellite links typically provide a high capacity for their international service.

Information Transmission Capability

Hard-line telephone systems can provide two-way voice and electronic communication.

When the system is used for communication between drivers and the control center, telephone machines and computer terminals are needed at both ends of the line for voice and electronic communication respectively.

When the system is used to link roadside readers and control center, electronic messages are sent one-way from the reader to the control center. In this case, special interface units are required between the readers and the telephone lines. At the control center, a computer terminal with a modem is used to receive the electronic messages.

Mobility

Hard-Line telephone lines are not mobile.

Cost

A general cost analysis of the hard-line system is provided in this section. The costs consist of equipment costs at both the dispatch center and telephone centers, and the network fees.

<u>Network Fees</u>: This includes the cost per call from a public telephone. Such fees depend on the destination and origin of the call and may be divided into three principle types: local, national and international. Local calls are made within one code area. National are calls made between two code areas. International calls are made between different countries. When the telephone lines are used to link roadside readers with the control center, the network fees is the cost of the lease of the lines.

Interface Unit Costs: This covers the cost of the interface unit used between the roadside readers and the communication system.

Control and Telephone Centers Costs: This includes the network fees and the cost of telephone machines, faxes, and data terminals at the dispatch or telephone center.

1) Hard-Line Network Fees: This includes the subscription and maintenance fees and the fees per call.

2) Telephone Machines' Costs: This is the cost of the telephone machines installed at the dispatch center.

4)Computer Integration Costs: This would cover the costs of computer software and hardware including modems that will be deployed at the control center and linked to its telephone system to send and receive electronic messages.

B.2 Paging Systems

Coverage

Coverage of such a system depends on the location of the transmitters and their geographic ranges. Some companies are starting to use satellite as a link between remote transmitter bases and their switching boards. Most paging systems provide national service and some companies are developing systems that would operate in more than one country. A transportation carrier might choose to subscribe to pager networks in other countries, so the dispatch center would have to call the switching board of the foreign pager network to send messages to the vehicles operating in that country.

Availability of Service

For service availability, the pager has to be within the range of the transmitters. Once the pager is reached by a transmitters signal, the high speed signaling of paging systems, about 1200 bits per second results in high availability and capacity of service (higher than cellular).

Information Transmission Capability

A pager can only provide one way communication. Information can only be sent from a telephone to the pager and not in the other direction. The early pagers only received a short voice message. More advanced pagers can receive short electronic and voice messages at a speed of about 1200 bit per second. To send electronic data, the control center has to be equipped with a computer system that can send electronic messages through the telephone lines.

Mobility

The pager system is usually mobile. A pager is a small portable device that can be carried with ease by the user at all times.

Cost

The cost of the system includes the pagers' cost and the dispatch center costs.

Pager Costs: This cost would include a subscription fee to a paging network for an interval of time. It would also include the cost of the pager.

1) Pager Network Fees: Pager fees are about $60 per pager per year. The carrier might consider to use pagers in other countries.

2)Pager Costs: This includes the cost of the pagers that are supplied to the drivers. The cost is around $200.

Control Center Costs: This would include subscription fee and the cost of telephone machines and computer terminals for the telephone line at the dispatch center.

1) Network Subscription Fees: This includes the subscription and maintenance fees and the fees per call for telephone services. Calls to pagers are usually of constant length and to one destination which is the switching board.

2) Telephone Machine Costs: This is the cost of the telephone machines installed at the control center.

3)Computer Integration Costs: This would cover the costs of computer software and hardware including modems that will be deployed at the control center and linked to its telephone system to send and receive electronic messages.

B.4 Two-Way Radio System

Coverage

The coverage of a single base depends primarily on the height of the transmitting and receiving antenna. If an area is reached by a weak signal, then having a powerful transmitter would improve the situation; however, if the area is not reached by the signal, then the only solution would be to change the position of the transmitter's antenna until the signal reaches the area. It is often more difficult to cover mountain and urban areas in comparison with planes.

As the area covered by a single land base increases, interference is more likely to occur because of the finite number of available frequencies and the number of other system users that increases as the area increases. Therefore, in order to cover a large area, a number of land bases can be spread out within this area and linked to the dispatch center by hard wire. In this situation, each land base would cover a smaller area in which more frequencies are available. Adjacent land bases transmit at different frequencies. Similarly, to cover remote areas, land bases can be setup and linked to the dispatch center through hardwire. In general, interference is less likely in rural areas; therefore, a lower concentration of bases is required in rural areas than in urban areas.

If private or shared, the coverage of such systems depends on the number of bases and their ranges. In urban areas, private and shared networks face certain difficulties, for instance the high cost and low availability of appropriate land bases and obtaining licenses or permission for such bases. In rural areas, sites are easier to find at a relatively low cost and permissions and licenses are easier to obtain. Another problem is the availability of hardwire links between the land bases and the dispatch center. Such hard-wire connections are typically leased by the private or shared radio networks. A national network typically has enough bases to cover the whole country , although some gaps may exist in rural areas. Although it is cheaper to cover rural areas, it is still not economical to build bases in some areas where very little traffic passes through.

Availability of Service

For the service to be available, the mobile radio has to be with in the operating range of the land bases.

Once the radio is with in the range of a land base, the availability of service mostly depends on the number of channels provided by the land base and the number of users at any one time. In two-way radio Systems, the user might need to wait until the channel or the frequency is free. As the range of the land base increases, interference from other radio systems (e.g. television) would reduce the number of channels available to the land base. Furthermore, as the area covered by each land base increases, the number of users of each land base at any one time will increase. This problem is greater in shared and public networks where the number of users is high in comparison with private networks. Availability and capacity in two way radio system is lowest among all the other alternatives.

Information Transmission Capability

The system can provide two-way voice and electronic communication between the terminals. For electronic communication, data terminals are required to be linked to the voice terminals. Data terminals are computer systems that are equipped with software and modems that allow users to send and receive electronic messages.

In-vehicle data terminals are mini-computers with reasonably sized screens and keyboards. A special interface unit is required to automatically take information from on-board AVL units to the in-vehicle data terminal.

Mobility

This is a highly mobile system. The mobile terminals are usually fitted in vehicles especially when linked to a data head.

Cost

The cost of the system covers the cost of infra-structure, fixed terminals and computer integration at control center, in-vehicle voice and data terminals and interface units.

<u>Radio Infra-structure Costs</u>: In case of private or shared network, this would include cost of equipment, structure, and land sites of base stations. It will also include the cost of the hardwire links to provide through put and coverage for certain areas.

In case of Shared or Private Network

1) Base Station Equipment and Structure Costs: Base station costs would consist of the cost of the transmitters, receivers, antennae, and the land base structure. Such costs range form $20,000 and 50,000 depending on the power and size of the station.

2) Base Station Site Cost: This covers the cost the site of the land base. The land site can either be leased or bought, and the costs vary between urban and rural areas.

3) Hardwire Links Cost: The hardwire link is typically leased from a communication company.

In the case of a national or public network, this cost would be a subscription fee per interval of time. The subscription fee is around $20 per year per terminal.

<u>Control Center Costs</u>: This includes the cost of the telephone machines or the fixed radio terminals that are installed at the dispatch center. Fixed radio terminals are used when a public or national network is providing the service or when the land bases are linked to the dispatch centers by radio in private or shared networks. Telephones are used when hardwire is used to link the land bases and the dispatch center in a private or shared

network. This would also cover the computer integration costs to allow or electronic data communication to and from the dispatch center.

1)Fixed Radio Terminals Costs: The cost of the fixed radio terminal that provide voice communication only is around $1500 per terminal.

2)Telephone Machines Cost

3) Computer Integration Costs: This would cover the costs of computer software and hardware including modems that will be deployed at the control center and linked to voice terminals to send and receive electronic messages.

In-vehicle Radio Terminal Costs: This covers the cost of the in-vehicle radio terminals that provide voice communication only. The cost is around $500 per terminal.

In-vehicle Data Terminal Costs: In order to receive and send electronic messages, the vehicles should be equipped with in-vehicle data terminal linked to a voice terminal. The cost of an in-vehicle data terminal depends heavily on its functions. The mobile data terminal consists of a terminal with a reasonable sized screen, a small keyboard and integrated message storage and processing capability.

In-vehicle Interface Unit: This covers the cost of the interface unit that is used to take information from on-board AVL units to the in-vehicle data terminals.

B.5 Radio Cellular Phone System

Coverage

Cellular phone service is usually obtained by subscribing to a cellular phone network. For this reason, the use of cellular phones is limited to the coverage of the providing network. Most cellular phone networks operate on a national or regional level with some gaps in rural areas.

Availability of Service

For the service to be available, the mobile phone has to be within the range of a cell site. Once the cellular phone is within a cell, the service would be provided by dedicating a free channel to the cellular phone while in use. The availability of service depends on the capacity of the system, which is the number of channels available per cell site, and the number of cellular phone users at the time. Having a shorter range per cell site would reduce interference from other radio systems such as television, and therefore increase the number of available channels available per cell. Further more, if the area of a cell is reduced, the average number of users in the cell at any one time will decrease. The range of cell sites is typically smaller than the range of land bases in the two-way radio systems; hence, the availability of the cellular system is better.

Information Transmission Capability

Cellular phones were primarily designed for the transmission of two-way real time voice messages and then developed electronic data communication. In addition to their access to other cellular phones, they have access to national and international public telephone networks through their switching board. For electronic communication, data terminals are required to be linked to the voice terminals.

The range of cell sites is relatively short especially in urban areas. Therefore, during a single phone call, it is not uncommon for a mobile phone to cross more than one cell. Adjacent cells have different frequencies, so as the vehicle crosses from one cell to another, the cellular phone switches frequencies automatically. At this moment, transmission might be interrupted for a very short interval of time. This discontinuity in transmission might not be a problem if the phone is being used for voice communication; however , if data is being transmitted electronically which usually takes place at a high speed , then such a disruption will result in the loss of data. A device called the bridge can act as a buffer storing data between the cellular phone and the mobile computer throughout transmission. Therefore, to transmit electronic data in addition to voice messages through cellular phones, the mobile phone should be linked to a data head by a bridge. Otherwise, the vehicle can be equipped with a cellular data terminal (which is also equipped with a bridge) that allows for electronic data transmission only. In either case, the dispatch center must be equipped with a computer integration system. If the cellular phone is fixed in one location, transmission of electronic data does not require a bridge.

Special interface units can be used to automatically take information from on-board AVL units into the in-vehicle data terminal.

Mobility

The mobile phone can either be fixed in the vehicle or carried by hand while the data terminal would be fixed in the vehicle.

Cost

The cost would include cellular network fees, cellular phone ,cellular data terminals, dispatch center telephones costs.

Cellular Network Fees: This cost is the fee paid to the cellular company in return of the cellular service. It includes subscription fees (around $11 per phone per month)and the fees per call (around $0.3 per minute).

Cellular Phone Costs: This would cover cost of the cellular phones which is around $400 per phone.

In-vehicle Data Terminal Costs: As for the two-way radio system, this covers the cost of the control head if the vehicle is already equipped with a phone or the cost of a cellular data terminal. It also includes the cost of the bridge.

In-vehicle Interface Unit: This covers the cost of the interface unit that is used to take information from on-board AVL units to the in-vehicle data terminals. The cost is around $500.

Control Center Costs: Telephones at the control center can either be cellular or hard-line telephones. In case of cellular phones, the telephone costs would the cellular network fees, the cellular phones costs, and a tone transformer if a fax machine is to be installed. There is no need for a bridge because the cellular phone would be stay in the same cell because it is fixed at the dispatch center. If the telephones at the dispatch center are hard-line phones then the cost of telephones would be the hard-line network fees and telephone machines costs. In addition to telephone costs, the dispatch center costs include fax machines and computer integration costs.

1) Hard-Line Network Fees: This includes the subscription and maintenance fees and the fees per call.

2) Telephone Machines' Costs: This is the cost of the telephone machines installed at the dispatch center.

3)Computer Integration Costs: This covers the cost of the software and computer system which would be installed at the control center to receive electronic messages from the in-vehicle terminals. If cellular phones are used at the control center, any computer can be linked to the cellular phones without a bridge.

B.6 Mobile Satellite System

Coverage

The coverage of satellite systems depends on the orbits and the number of satellites deployed. Some systems provide world-wide while others provide continental services.

Availability of Service

For mobile satellite telephone service to be available, the mobile phone has to be with in the geographic are covered by the satellite system. Once the phone is in a covered area, service availability depends on the number of satellites deployed and the number of users at any one time. The availability of the satellite service is one of the highest among all available communication systems.

Information Transmission Capability

For information transmission, the system offers a service similar to that of radio cellular telephones. It provides two-way real time voice communication from any covered area to anywhere in the world.

The system can also be used to send electronic messages and status information. In the same manner as for two-way radio systems, data can be transmitted through the system if the mobile phones are linked to in-vehicle data terminals and if the control center is equipped with the appropriate software and computer system. The system does not require the bridge that is used for the mobile data terminals of the cellular system. Special interface units can be used to automatically take information from on-board AVL units into the in-vehicle data terminal.

Mobility

The mobile satellite phones are fixed in vehicles.

Costs

The costs would cover satellite network fees and satellite telephones, in-vehicle data terminals, and control center costs.

Satellite Network Fees: This includes subscription fees (around $600 per year per phone) and fees per call.

Mobile Telephone Costs: This would also include the cost of the mobile phones.

In-vehicle Data Terminal Costs: This covers the cost of the in-vehicle computer system that can be linked to the mobile satellite telephone to allow for electronic communication.

In-vehicle Interface Unit: This covers the cost of the interface unit that is used to take information from on-board AVL units to the in-vehicle data terminals.

Control Center Costs: Telephones at the control center can either be satellite or hard-line telephones. In case of satellite phones, the telephone costs would the satellite network fees and the satellite phone costs. If the telephones at the dispatch center are hard-line phones then the cost of telephones would be the hard-line network fees and telephone machines costs. In addition to telephone costs, the control center costs include computer integration costs.

1) Hard-Line Network Fees: This includes the subscription and maintenance fees and the fees per call.

2) Telephone Machines' Costs: This is the cost of the telephone machines installed at the dispatch center.

3)Computer Integration Costs: This covers the cost of the computer software and hardware including modems which would be installed at the control center to receive and send electronic message.

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