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High Accuracy Location Based Services Cost Benefit Study: Final Report

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I. Executive Summary

This report presents a benefit and cost study of a Cooperative High-Accuracy LOcation (C-HALO) service. The Department of Defense operating the GPS constellation guarantees a location service accurate to 7 meters 97% of the time. Using this as a baseline, we define the High Accuracy Location service to be sub-meter (alternatively, decimeter) level accuracy. This report is about the costs and benefits of realizing a location service with sub-meter accuracy in the United States.

There are several GPS augmentation technologies aimed at enhanced accuracy. Some such as Inertial Navigation Units are on the rovers and entail no new infrastructure. Others such as DGPS, N-RTK or HAN-DGPS, build new infrastructure to assist new rover units. In our definition, these augmentations only constitute a high accuracy location service, if they entail a promise like the one provided by the DoD for the GPS constellation, e.g., Infrastructure X provides a location service accurate to 1 meter or better Y% of the time. A High Accuracy Location service should be ubiquitous and reliable, like its LALO[1] equivalent, the GPS constellation.

The business model of the Inertial Navigation Unit industry envisages no such guarantee. The ubiquity of any higher accuracy outcome of GPS/INS fusion is left entirely to the purchaser of the unit, if anybody at all. On the other hand, our literature and market survey suggests, the N-RTK market does entail guarantees or promises like the one from the DoD for GPS. The N-RTK service providers seek to assure customers that the ubiquity or reliability of their high accuracy location service will be adequate. HAN-DGPS is a public sector infrastructure build that could also provide assurances. Hence this report discusses the details and salient features of these infrastructures. We do not study the INS industry.

We have surveyed the literature on location services, and discovered a body of work on the benefits of a high accuracy location service. The literature establishes the benefits of high accuracy location to industries such as agriculture, construction, mining, and aerospace. Chapter III summarizes this literature. We focus on road travel and the findings suggest this focus is worthwhile. Chapter IV of this report quantifies the benefits of HALO services to road travel, and estimate benefits to be between $160 billion and $320 billion. This translates into 1.1 to 2.2 percent of the current US GDP. The estimated benefits are gross benefits over a time horizon of 22 years discounted to the present day value. They do not account for the costs of implementation. The range depends on whether one uses the low-level or mid-level efficacy assumptions. The benefits arise from smoother traffic flow on the roads leading to reduced travel delays, and fewer accidents leading to reduced injuries and saved lives. We expect HALO to also yield climate-change and public health benefits through its enabling of smoother traffic flow but have been unable to quantify these benefits for this report.

The assessment of the costs associated with these benefits has two challenges. One must assess where new infrastructure is required and how much each installation might cost. To understand where HALO

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[1] Low Accuracy LOcation

services need new infrastructure it helps to think of places with “good” GPS coverage as distinct from “bad” GPS coverage. This is the subject of Chapter V. The chapter presents a way to process data from a county assessor’s office and divide the county into good and bad GPS areas. The method is illustrated by application to San Francisco. When 6 or more satellites are visible and they are well spread out, GPS accuracy is good and enhancements such as N-RTK or HAN-DGPS make it even better, resulting in decimeter or even centimeter level accuracy. When the number of GPS satellites is lower, GPS errors can be over a meter and these augmentations are less effective. Some other kind of technology, perhaps pseudolites, is required. We call the area not well served by the GPS constellation, the “bad GPS” area or “dark area.” We expect tall buildings in urban areas to reduce satellite visibility on streets. Likewise, tall trees can occlude satellites. Thus urban canyons or parkways in wooded area would be part of the dark area or bad GPS coverage areas.

The existence of the N-RTK market makes the distinction between good and bad GPS areas useful. Since N-RTK realizes HALO in good GPS areas, HALO services for good GPS areas are more advanced than HALO services for bad GPS areas. There are no significant location services sold in the US consumer market for bad GPS areas. Therefore the work in chapter V computing the percentage of the road area that is “good” and “bad” GPS coverage provides insight into how much of HALO needs fundamentally new location infrastructure that is not GPS augmentation, and how much could potentially be achieved by leveraging GPS augmentation methods such as HAN-DGPS or N-RTK market.

Finally, for good GPS areas, chapter V presents infrastructure cost numbers based on N-RTK. There are enough N-RTK deployments to collect and compare these numbers. We assess the current cost to be $560,000 to $1.6 million per base station over a time horizon of 22 years covering a 60x60 sq.km area. A simple linear scaling, puts this at 1.6 to 4.4 billion nationwide, of the order of 1% of the benefits of HALO estimated to accrue from road travel alone. We have been unable to do the same for bad GPS areas.

The good and bad GPS coverage classification method in chapter V is GIS based. It produces a map with good and bad areas marked on it. Other GIS data can be over-layed to visualize the value of enabling HALO services in a particular place. We overlay accident data. One can spot the bad GPS streets coincident with higher accident rates. The idea is to spot the streets where one gets a bigger bang for the buck. The other good news in our findings, is that out of the total 121 sq km. area of San Francisco (121 sq.km), only 0.3 to 4% of the San Francisco streets fall in the “dark” area. This range is the 95% confidence interval. Since the dark areas are few and we can spot them, one can target new investment to areas yielding safety or mobility benefits. If an area is estimated by us to be dark, we know new high accuracy location infrastructure beyond GPS augmentation methods is required with high confidence. Our model does not say the converse with high confidence, i.e, GPS augmentation technologies like N-RTK will work in the “light” areas. This is because even in the “good” GPS areas with sufficient satellite coverage the errors can be quite large due to multipath effects.

II. Motivation

The study is motivated by the possibility of the benefits of High Accuracy (sub-meter) Location being large, such a service being technologically feasible, and deployable at reasonable cost.

The high benefit argument rests on research showing vehicle-based collision avoidance systems can reduce accidents (8). The systems require location services accurate enough for a vehicle to discriminate its lane, which in turn requires sub-meter accuracy (30). Likewise high-speed tolling or intelligent traffic light control also requires lane discrimination and sub-meter accuracy. Since the economic cost of lives lost in accidents is high as is the economic cost of delays due to traffic congestion, the benefits of HALO as a critical enabler of services mitigating accidents or congestion should also be high.

The technological feasibility argument rests on the proliferation of GNSS[2] systems and services. GPS has become a stable component of global economic activity. Other GNSS such as GLONASS and Galileo, are becoming established. Technologies such as DGPS, GPS-WAAS, GPS+INS, GPS-RTK, and Network RTK(2,3) have been developed and partially deployed in recent years. Limited-coverage pseudolite-based systems are also available (61-63). Ultra Wide Band systems coupled with RTK (66,67) are being proposed to achieve high levels of accuracy in multipath rich environments. Wide-area multi-lateration systems (4) are being substantially deployed around airports for aircraft and ground vehicle tracking. Inertial Navigation Systems are rapidly dropping in cost even as the rise in accuracy. All of these suggest there may be many options in the market or near-to-market that might be leveraged to realize a ubiquitous and reliable HALO service.

Many of these new location options will rely on the ubiquitous availability of mobile communication services. HAN-DGPS requires ubiquitous broadcast communication from base station to mobile, and N-RTK ubiquitous unicast communication between infrastructure and mobiles. Here too the rise of 3G, 4G (65), Dedicated Short Range Communications (DSRC) (64), software defined radio (5), smart antenna systems (6), and other techniques, along with use of vehicles as excellent mobile communication platforms (7), may provide for advancements in positioning techniques and integrated systems.

The market analysis and literature review section indicates a lack of coverage of the benefits of C-HALO technology to the Transportation domain in general and ITS in particular. From the literature presented, efforts exist that attempt to quantitatively estimate the costs and benefits of high accuracy location data. These efforts are mostly market wide, or specific to an individual industry that is not transportation. In addition, plenty of literature exists to understand the costs and benefits of implementing certain ITS applications like curve speed warnings (8), or intelligent signal control systems (9). This later effort usually addresses the particular application under study and does not analyze the monetary benefits to the market; their results are presented in number of accidents reduced or total vehicle miles saved by the deployment of the application.

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[2] Global Navigation Satellite System

This lack of coverage of the transportation industry motivates us to tackle the job of estimating the economic benefits that could be reaped from a C-HALO nationwide deployment to the ITS sector of the transportation domain. It is the objective of this analysis to develop an exhaustive list of ITS applications that require high accuracy location data to realize the costs of implementation and the expected economic benefits that accompany each application.

This study aims at providing a tool enabling government and private funding agencies to assess the benefits of investing in a new breed of positioning technologies and wide-scale deployments to meet the goals first noted above. It will shed light on the range of costs of the most promising technologies, their integration, and phases of deployments leading to a nationwide C-HALO infrastructure.

III. Literature Summary

We have reviewed existing GNSS related market analyses and cost benefit studies done by others on various sectors of the economy and in various parts of the globe. This section summarizes our findings.

A. Market Analysis

Rob Lorimer of Position One Consulting performed a three year projection on the GNSS global market in his report titled: GNSS Market Research and Analysis September 2008 (10). Based on this report and analysis, we created a table of global positioning companies, along with which industry(ies) each company is involved in. The complete table is included as Appendix A.

The table identifies the three most ubiquitous providers of GNSS-based services as Leica Geosystems, Trimble, and TopCon/Sokkia. Omnistar is also relevant in many industries, but they are mainly focused on precision augmentation services, while the other three are more vertically integrated, and typically incorporate numerous levels of the value chain. Interviews conducted by Lorimer with the CEO's of the companies listed in Appendix A (10) provided insight into the industries that are major consumers of location services. The biggest consumers are the Aerospace, Agriculture, Autonomous Vehicles, Construction, Defense, Maritime, Mining, and Surveying industries. Clearly void from this list is the transportation sector, which we choose to analyze as part of this CBA. Benefit estimates have been completed in some of these industries and are discussed in more detail in the subsequent section.

B. Published Benefit Analysis Reports of Various GNSS

The Allen Group (11) estimated the economic benefits of C-HALO type technology in three specific Australian industries: Agriculture, Mining, and Construction. The Allen Group determined the benefits to be between \$100 and \$200 billion, approximately 10 to 20 percent of Australian GDP. These three markets make up approximately 10 to 13 percent of GDP. Assuming that the U.S. transportation market makes up 5 percent of GDP, a simple linear scaling of the Allen Group's numbers suggests the HALO benefits derived from the transportation sector alone should be 4 to 9 percent of GDP, which would be approximately \$560 to \$1.2 billion in benefits. We find \$160 to 300 billion. These benefit numbers appear conservative in relation to the Allen Group study.

We have incorporated a key piece of the Allen Group report in our method. The adoption rate for the C-HALO technology is represented by this studies' industry-wide national rollout adoption scenario.

A socio-economic benefit study was commissioned by US Department of Commerce (DoC) (12) to determine where there is value added by the CORS and GRAV-D systems. The study is focused on the benefits derived from the increased vertical accuracy of GPS. We do not consider this dimension at all. The study suggests the surveying and mapping industry will be the most significantly impacted, but goes on to list other possible industries like construction, agriculture, environmental science, and transportation. Again this reiterates the fact that researchers are continuing to view transportation as a realm for potential benefits from C-HALO technology. The US DoC study assesses benefits utilizing the productivity methodology, which is typical and similar to the methodology used in our study and many others contained in the literature review. One slight difference to our methodology is that their time horizon is 15 years while ours is 20 years.

Alcantarilla, et al. analyze the benefits of a multi-constellation system, versus a stand-alone GNSS system, and ultimately a SBAS approach (14). A piece that may be of importance to us when discussing the costs is the distribution of the number of satellites in view. They conduct a simulation of an urban environment and contend that with GPS & Galileo 65% of the area is covered by more than 3 satellites, while 20% is covered by 3, and 15% by less than 3. They then go on to qualitatively discuss the principal pieces of a future GPS system along with the envisioned benefits of multi-constellation GNSS SBAS augmentations. Similar analysis is carried out by Zabic et al. (68) but with actual data in Copenhagen. They estimate the average satellite availabity in Copenhagen through extensive data collection and use simulation tools to predict the improvement in satellite availability with the addition of Galileo.

Swann, et al. discuss the qualitative benefits of location-based services, the architectural issues involved in multi-constellation systems, and the market aspects that need to be addressed for deploying multi-constellation systems (15). They focus on the benefits of reliability of a combined GPS/Galileo signal where availability is at 99.7% in their Stuttgart analysis. In addition, they estimate the GNSS service provision market to be 135 billion Euros by 2015 with a significant portion of that residing in the transportation industry. This is significantly higher than what Lorimer's report quotes for the U.S. market by 2012, which is around $9 billion.

Vollath, et al. aimed to look at how NRTK and the third frequency to be offered by Galileo will interact (16). Vollath et al. present the value of the Galileo third frequency in allowing higher horizontal accuracy and increasing distances between base stations among other things. NRTK, however, still proves to be more accurate in the vertical direction. Ultimately, they do not assess the monetary benefits, but only the technical reliability. They conclude that NRTK will not be replaced by the Galileo new third frequency, but that the two could be used as complimentary technologies.

Arthur, et al. delve deeper into the impacts of Galileo by going beyond cost benefit analyses and conducting specific input-output models (17) which actually predict economic output rather than just analyzing costs and benefits. They even go as far to suggest that some 'market externality' impacts, like induced effects, could be twice as large as the direct impacts. They also suggest how to enhance a CBA by including innovation effects (through supply-push or demand-pull forces), or market and social externalities. These types of analyses could be worthwhile as future work. They are not included in this report.

Brennan, et al. wrote National PNT Architecture: Interim Results to facilitate the decision making process on a national PNT architecture for the United States by 2025(18). It does not focus on costs or benefits in quantitative terms. It does however evaluate many different technological options to achieve their stated goals. Ultimately, they want to put together a transition plan from an "as is" architecture to a "should be" architecture. Unfortunately, this is not directly related to our CBA.

C. Existing C-HALO Type Deployments

In order to understand the existing C-HALO deployments and technologies, we reviewed the initiatives undertaken by the government agencies. The material here is based on reports (56) and (59) provided by the Federal Highway Authority. The earliest deployments were the Differential GPS (DGPS) base stations by the US Coast Guard for maritime services. These base stations broadcast the actual and measured pseudo-range differences of the received code measurements from the different satellites. These error measurements are used by GPS receivers to calibrate their own measurements resulting in accuracies as high as 1m under good line-of-sight conditions. The corrections are broadcast typically in the longwave frequency range between 285kHz and 325kHz. The U.S. Army Corps of Engineers (USACOE) later realized the benefits of accurate localization and efforts were made to increase the coverage of the DGPS base stations (56). This resulted in the N-DGPS or nationwide DGPS program under which a total of around 137 base stations were to be installed nationwide to provide accurate localization services. The defense establishment also found need for decimeter and centimeter level accuracies. This could be obtained by sending corrections to the carrier phase received by the DGPS stations, as the carrier frequency of GPS is 1000 times higher than the frequency of the modulated code sequence. Hence one could obtain very high accuracies by measuring the carrier phase. This technology came to be known as RTK or Real Time Kinematic positioning and the proposed system implementation by government agencies has come to be known as HA-NDGPS – High Accuracy NDGPS (56).

One of the challenges of HA-NDGPS is that the allocated bandwidth does not suffice for broadcasting the carrier measurements for all the satellites (59). This requires compression of the phase measurements. This work is still in progress. Prototypes of this system were deployed and evaluated (56). During deployment it was found that, if a receiver obtained corrections from more than one base station, a combination of the measurements provided higher accuracies. More sophisticated combination could provide still higher accuracies, and this is the proprietary technology used in N-RTK or Network RTK, a service, provided by companies such as Leica, Trimble etc. The N-RTK service has two methods of operation (71). The Virtual Reference Station (VRS) method as adopted by agencies like Trimble is a unicast system where the GPS receiver contacts a central server, which in turn computes the corrections from the set of receiver stations in the vicinity of the receiver and gives an estimate of the receiver's location. The Master Auxiliary Concept (MAC) method allows for a broadcast system wherein a single master reference station amongst a cluster of reference stations in a cell, broadcasts the corrections. The rover in turn interpolates these corrections to estimate the corrections at its location. The MAC method also allows for a two-way mode where the reference station calculates the corrections for the rover as in the case of VRS. In our opinion, the question of whether one would want to adopt a unicast system or a broadcast system depends on the application. For a large-scale application like Intelligent Transportation Systems, it might be desirable to have a broadcast system and have all the intelligent processing done at the GPS receiver as compared to a central server. If every vehicle is required to know its location accurately, it is more efficient to broadcast the error measurements to all the vehicles in contrast to every vehicle contacting a centralized server to compute its location estimate since the error measurements would be common to all the vehicles in a particular region of interest.

HA-NDGPS is the technology that is being standardized by the federal DOT as the technology of choice for achieving high accuracy positioning for ITS applications. The federal DOT has commissioned a couple of pilot programs to improve on this technology to achieve cm level accuracies nationwide. The pilot sites are in Maryland and Pennsylvania and the research is being headed by the Turner Fairbanks Highway Research Center. The current and planned coverage areas are in the map below:

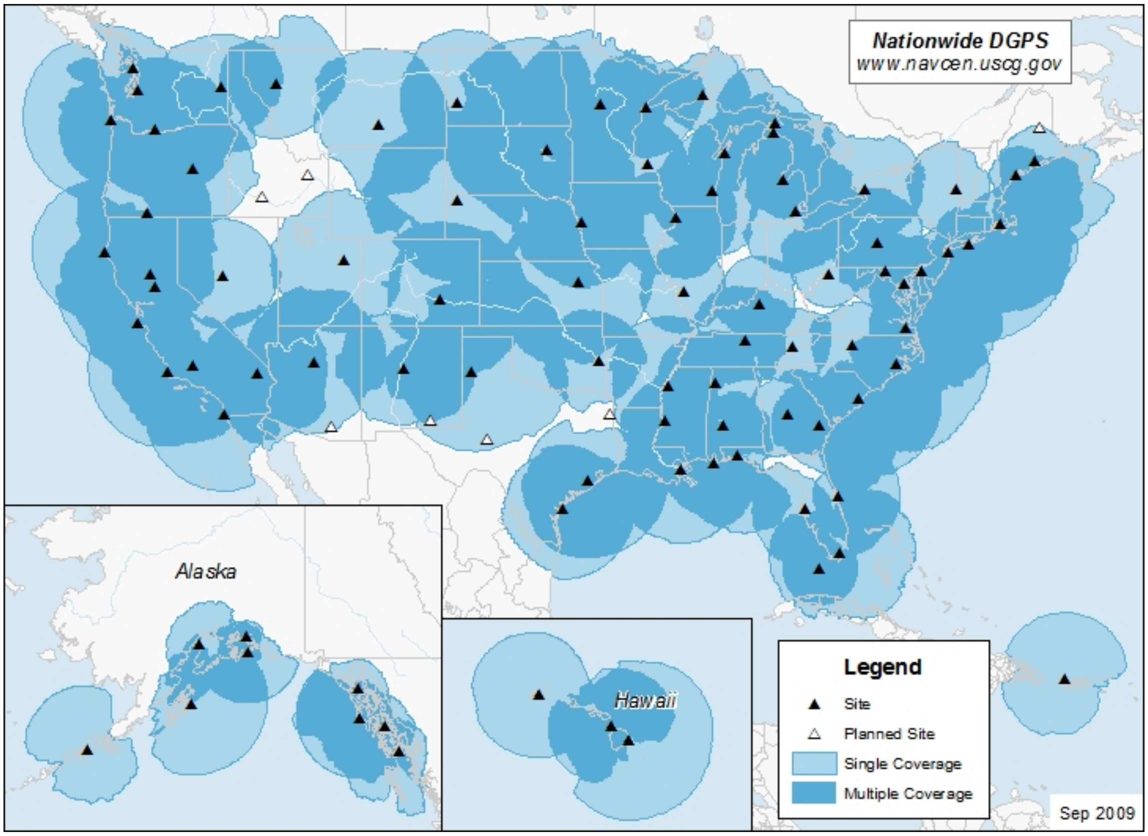

Figure 1 HA-NDGPS Coverage Area

Additionally, we have researched state run, cooperative and private run positioning and augmentation services. Most of these services are N-RTK corrections. Figure 2 shows the states with N-RTK deployments we have found as of December 2010.

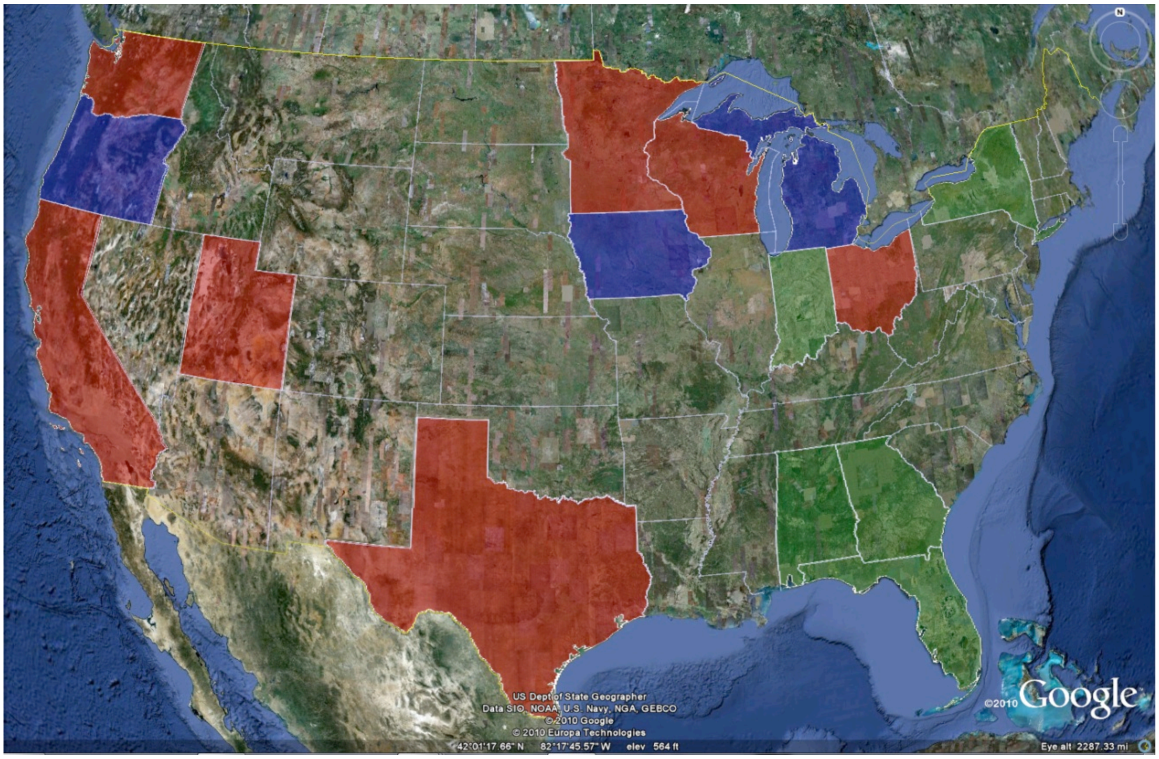

Figure 2 N-RTK Deployments Reviewed (36 – 46)

The red states denote N-RTK deployments partnered with Trimble, while the blue states denote N-RTK deployments partnered with Leica. The green states partners were either unidentifiable or only explored, but never actually deployed, an N-RTK the network. Within this group of states the State run programs and Private/Public Cooperatives are as follows:

Table 1 State N-RTK Deployments (36 – 46)

State DOTs	**Public/Private Cooperatives**
Utah	Texas
Ohio	Washington
Iowa	Midwest (Indiana)
Oregon	Alabama
California	
Michigan	
Minnesota	
Wisconsin	

Throughout these deployments there are many similarities in infrastructure. The first implementations were in the early 1990s and have continued through the 2000s. From an infrastructure standpoint the industry standard seems to place N-RTK base stations 60km to 70km apart. Most of the deployments have from 50 to 80 base stations. Some of the cooperative deployments continue to grow due to increasing membership, and in addition, some of the nascent state DOT's deployments also have expansion plans in place. All of the deployments offer centimeter level accuracy within their network. (36 – 46)

The networks differ in their access rules. Currently all state DOT networks charge no fee for usage, except for Utah, which just changed policies and began charging $400 annually. The cooperative networks typically charge between several hundred and several thousand dollars annually. On top of this, users must purchase a receiver and applicable cellular plan for the data flow. Cellular plans typically range in the order of $100 while receivers range from several hundred to several thousand depending on capability. (36 – 46)

These costs seem bearable by markets such as Agriculture, Surveying, and Construction services, due to their high use of these state-run and cooperative networks. Only one state, Minnesota, had implemented and deployed N-RTK for transportation purposes. They use the network for snowplows and inner city bus routes. (42)

Three states were questioned for cost information: Iowa, Ohio and Washington. These systems range between $50K and $115K in expenditures per base station to perpetuity. These costs are discussed in further detail in a separate chapter.

To gain further understanding of the availability of C-HALO services, we review private services offered by Omnistar and Leica. (47,48 & 49)

Leica has SmartNet, which is N-RTK coverage, in many states across the United States. Based on SmartNet's service agreement (54, 55), Leica offers 1-2 cm horizontal accuracy and 2-3 cm vertical accuracy under conditions of good satellite coverage, good geometry, and low multipath environments. However we have not been able to locate, from Leica, the percentage of time those conditions are satisfied within their areas of coverage. The map below documents many of the states in which Leica has some private coverage available. Typically this coverage is provided through private investment, and partnerships with other Leica network deployments. The service agreement (54) explicitly mentions that Leica geosystems disclaims warranty to the accuracy of the data created by or passing through the SMARTNET Reference Station Network. Omnistar currently claims 99% availability of C-HALO services in the United States. This is offered using DGPS technology and entails an annual subscription service as well as investment in a GPS receiver. The subscription services range from $800 for the least accurate (sub-meter) to $2500 for the most accurate (centimeter) per receiver. The receivers generally cost around $5000 and are available from Trimble, Novatel, Raven, Topcon and others (50).

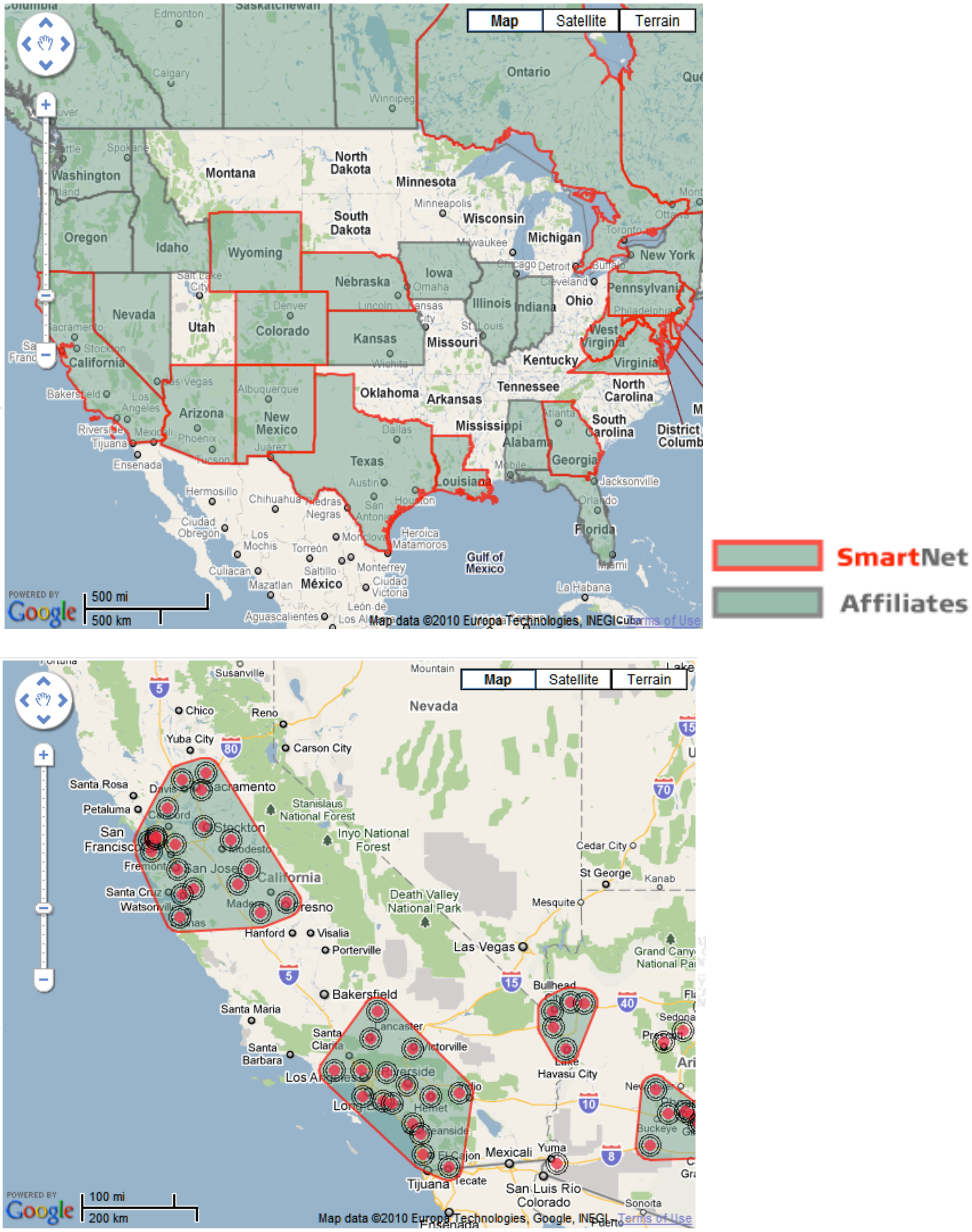

Figure 3 Leica N-RTK Service Area map (lower portion show covered spots in a three states: California, part of Nevada and part of Arizona).

IV. Benefit Assessment

Our approach is to determine a suite of ITS applications that require a high accuracy location service, find the benefits of these applications, and associate them to C-HALO. The ITS applications analyzed are those listed by the FHWA (19). A comprehensive list of these applications appears in appendix B. This list is analyzed for its location accuracy requirements. This filters down the application list to 8 groups of applications. If the applications require 1m or less accuracy, the applications and their benefits are analyzed, and associated to C-HALO.

Each application is explored independently to determine the efficacy rate, and the monetary benefit from reducing accidents (and in turn injuries and fatalities), VMT, travel times, emissions, and the like depending on the application. This type of methodology is similar to those used in other CBA's completed by the USDOT and other international governmental agencies. The method we use takes into account the cash flow estimates of the benefits over a 22 year period, and discounts those into "today's" worth via a discount rate that is proposed for this type of analysis by the congressional budgetary office. The analysis is similar to that adopted by the Allen Group (11).

The final list of applications can be seen in the Table 2 below:

Table 2 ITS Applications that Benefit from C-HALO Deployment

ITS Applications	Type	Included in Benefit Analysis
Curve Speed Warning	**Safety**	**Y**
Forward Collision/Braking Warning	**Safety**	**Y**
Emergency Electronic Brake Lights		
Cooperative Forward Collision Warning		
Merge/Lane Change Applications	**Safety**	**Y**
Highway Merge Assistant		
Lane Change Warning		
Blind Spot Warning		
Blind Merge Warning		
Left Turn Assistant	**Safety**	**Y**
Stop Sign Movement Assistant	**Safety**	**Y**
Highway/Rail Collision Warning	**Safety**	**Y**
Intersection Collision Warning	**Safety**	**Y**
Corridor Management	**Mobility**	**Y**
Intelligent Traffic Flow Control		
Free-Flow Tolling		

A. Assumptions

Some overall assumptions have to be made to estimate the benefits. Overall assumptions cover predictions we make about the national economy into the next 20 years, and general assumptions on how the new technology would be adopted by the ITS sector. We later on make application-based assumptions to estimate the particular efficacy of each application.

Technology Adoption Rate – The shape of this curve determines how quickly the fleet will adopt new technology, in this case C-HALO. The s-curve used in this analysis is leveraged from a report, by the Allen Group (11), which analyzes the benefits of high accuracy location data in non-ITS industries. The general shape of the curve is in Figure 4.

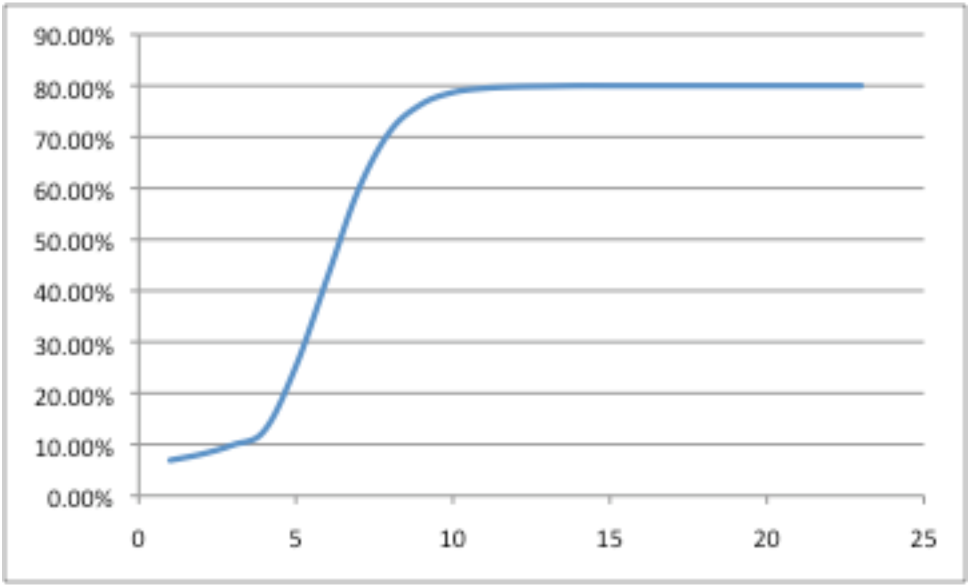

Figure 4 Technology adoption curve

This curve is applied over a project horizon of 22 years, 2008 – 2030. In calculating benefits, this adoption rate was typically used to determine the correct portion of benefits accumulated in a given year.

Discount Rate – This rate is used to discount future cash values to current day terms by taking into account inflation and a risk free rate of return, the higher the rate the more significant the discount to future cash values. For this analysis, a discount rate of 5 percent is used, and is taken from the Office of Budget and Management (20). They also suggest using a range from 3 to 7 percent.

Value of Time – The value of time is used in quantifying reductions in delay into monetary benefits. Again, the Volpe study quotes two figures, one for local travel, $11.20, and the other for intercity travel $15.60. These figures are from guidance from the office of the Secretary of Transportation (21). In our analysis, we take both figures and average them since in our data. The resulting figure is $13.40.

Delay Growth – The delay growth is calculated using figures from the Traffic Congestion and Reliability Report prepared by Cambridge Systematics for the FHWA in 2005 (22). Using twenty-year historical data (hours of delay per traveler) and trend analysis a growth rate of 6.5 percent is calculated.

B. Sources of Data

Accident Data – For the Safety applications, all accident data is culled from the GES database (35), which includes all types of accidents, not just accidents including fatalities. This database is then queried to ensure the appropriate accidents are being accounted for with regards to each individual application. Please see Appendix C for the querying methodology for each application class. We have also examined the FARS database (23) which includes fatal accidents.

Accident Growth Rate – The accident growth rate is used to project accident counts for years 2009 – 2030. The Volpe VII report projects accident rates based on VMT estimates and increased safety measures. These yearly accident rates are used to calculate the compound annual growth rate over the project horizon (21) This rate is calculated to be -0.2 percent.

Fatality Worth – This value is used in determining the benefit of reducing the count of fatal accidents. The Office of Management and Budgets put forth a memorandum in 2008 that suggests to the DOT that $5.8 million be used for the value of a life. It also suggests using a range of $3.2 million to $8.4 million (24).

Injury Worth – These values are based on percentages of the fatality worth. Again there is a standard, and that is the Maximum Abbreviated Injury Scale. Typically there are 5 injury levels not counting a fatality (24). In the FARS database only three levels of injuries are reported not counting fatalities. Therefore averages were taken first and second level and the third and fourth levels to determine the three percentages used in this analysis. The percentages used are in Table 3.

Table 3 Injury Worth Percentages

Injury Worth (% of Fatality Worth)	
Incapacitating	47.50%
Non-Incapacitating	5.80%
Possible/Light Injury	0.90%

C. Safety Applications

As part of the safety analysis, seven applications are analyzed: Curve Speed Warning, Forward Collision Warning, Merge/Lane Change Warning, Left Turn Assistants, Stop Sign Movement Assistant, Highway/Rail Collision Warning, and Intersection Collision Warning. All of these applications are focused on reducing accidents, and in turn fatalities and other injuries.

1. Curve Speed Warning

Curve speed warnings would aid drivers in negotiating curves at appropriate speeds. This is aimed at reducing single and multi-vehicle accidents in curves due to unsafe speeds.

To quantify the benefits of such a system we aimed to determine the number of accidents that could be reduced, then by using the assumptions laid out in previous sections, calculate a monetary benefit for reducing accidents.

To begin this process, the GES database was queried for specific accident data related to the application in question. For instance, all accidents that took place in curves, and were related to speed were included in this analysis.

In 2008, there were 1048 fatalities, and ~29000 other injuries where this type of application may be applicable. To determine the benefit of this system an efficacy rate must be determined to see how much of a reduction from these figures can be expected.

Through another literature review, several reports were found discussing how effective curve speed warnings could be. The three reports and results are summarized briefly below:

- Field Evaluation of the Myrtle Creek Advanced Curve Warning System (Oregon DOT 2006) – Empirical analysis of I-5 implementation near Myrtle Beach, over 75 percent of people reduced speeds entering the curves with dynamic message signage. The FHWA report (21) uses this value as a measure of efficacy of the curve speed warning applications when assessing the benefits of wireless communication to ITS.
- Rural ITS Toolbox (FHWA 2001) – Empirical study for trucks in Colorado. Speeds were reduced by 25 percent.
- An Evaluation of Dynamic Curve Warning Systems in the Sacramento River Canyon: Final Report (CA DOT 2000) - Empirical analysis of five locations on I-5 in California, over 70 percent of people reduced speeds entering the curves with dynamic message signage.

Using these sources as references, we chose to use 40% accident reduction as a mid-level efficacy rate. A low level would be 20% while a high efficacy level would be 70%. For a matrix of the efficacy rates please see Appendix D.

With all of this data, a discounted yearly monetary benefit can be calculated. The equation would as follows:

$$B = (EffRate_j * Adopt_n * \sum (InuryCount_{i,n} * Injury\%_i * FatalityWorth)) / DiscountFactor_n$$

Where B is monetary benefits, n is the year, j is the application, and i is the injury level (fatal, serious, etc.).

Using this formula and the low efficacy rate, preliminary benefits of ~$54 Billion were estimated.

2. Forward Collision Warning

Forward collision warnings alert a driver when a forward vehicle brakes hard (deceleration is above a predetermined threshold). This is very similar to Cooperative Forward Collision Warning which is used to preemptively avoid rear-end collisions with vehicles in front of the subject vehicle.

To quantify the benefits of such a system we aimed to determine the number of accidents that could be reduced, then by using the assumptions laid out in previous sections, calculate a monetary benefit for reducing accidents.

To begin this process, the GES database was queried for specific accident data related to the application in question. For instance, all accidents that took place in curves, and were related to speed were included in this analysis.

In 2008, there were 241 fatalities, and ~109000 other injuries where this type of application may be applicable. To determine the benefit of this system an efficacy rate must be determined to see how much of a reduction from these figures can be expected.

Through another literature review, several reports were found discussing how effective forward collision warnings could be. The three reports and results are summarized briefly below:

- Evaluation of an Automotive Rear-End Collision Avoidance System (Volpe 2006) – A study that analyzed data from a field operation test and the results suggest that 10% of all rear-end collisions could be reduced.
- Integrated Vehicle Based Safety Systems: A Major ITS Initiative (FHWA 2005) – A study on IV systems that suggests these types of applications could reduce rear end, run off road, or lane change collisions by 48%.
- The Evaluation of Impact on Traffic Safety of Anti-Collision Assist Applications (Sala, Gianguido & Lorenzo Mussone, 1999) – A simulation study that suggests between 10 and 60% accident reduction could be attainable depending on the adoption rate of the technology. This is very interesting and one of the only studies that addresses changes in effectiveness due to technology adoption.

Using these sources as references, we chose to use 25% accident reduction as a mid-level efficacy rate. A low level would be 10% while a high efficacy level would be 50%.

With all of this data, a discounted yearly monetary benefit can be calculated. The equation would as follows:

$$B = (EffRate_j * Adopt_n * \sum (InuryCount_{i,n} * Injury\%_i * FatalityWorth)) / DiscountFactor_n$$

Where B is monetary benefits, n is the year, j is the application, and i is the injury level (fatal, serious, etc.).

Using this formula and the low efficacy rate, preliminary benefits of ~$28 Billion were estimated.

3. Merge/Lane Change Warning

These warnings would alert vehicles on highway on-ramps if another vehicle is occupying its merging space (or in its blind spot). This is similar to Blind Merge Warning where warnings are used for vehicles attempting to merge with limited sight distance, and another vehicle is predicted to occupy the merging space. In addition, this system could warn the subject driver if a lane change is likely to cause a collision, triggered by turn signal activation.

To quantify the benefits of such a system we aimed to determine the number of accidents that could be reduced, then by using the assumptions laid out in previous sections, calculate a monetary benefit for reducing accidents.

To begin this process, the GES database was queried for specific accident data related to the application in question. For instance, all accidents that took place in curves, and were related to speed were included in this analysis.

In 2008, there were 13 fatalities, and ~3500 other injuries where this type of application may be applicable. To determine the benefit of this system an efficacy rate must be determined to see how much of a reduction from these figures can be expected.

Through another literature review, several reports were found discussing how effective merge or lane change warnings could be. The four reports and results are summarized briefly below:

- Integrated Vehicle Based Safety Systems: A Major ITS Initiative (FHWA 2005) – A study on IV systems that suggests these types of applications could reduce rear end, run off road, or lane change collisions by 48%.
- Freightliner to Offer Collision Warning on New Truck Line (Inside ITS 1995) – Empirical study of Transport Besner Trucking Co, which reduced its at-fault accidents by 34%.
- Dutch Field Operational Test Experience with "The Assisted Driver" (Alkim, Boostma, and Hoogendoorn 2007) – Empirical study of 20 vehicles in the Netherleands equipped with warning systems which were driven for five months. It found that unintentional lane changes were reduced by 35% on arterials, while it was reduced by 30% on highways.
- Run-Off Road Collision Avoidance Using IVHS Countermeasures: Final Report (NHTSA, 1999) – A simulation study that looked at lane departure warnings. Suggests passenger vehicle lane departures would decrease by 10%, while heavy trucks would decrease by 30%.

Using these sources as references, we chose to use 35% accident reduction as a mid-level efficacy rate. A low level would be 15% while a high efficacy level would be 60%.

With all of this data, a discounted yearly monetary benefit can be calculated. The equation would as follows:

$$B = (EffRate_j * Adopt_n * \sum (InuryCount_{i,n} * Injury\%_i * FatalityWorth)) / DiscountFactor_n$$

Where B is monetary benefits, n is the year, j is the application, and i is the injury level (fatal, serious, etc.).

Using this formula and the low efficacy rate, preliminary benefits of ~$2.1 Billion were estimated.

4. Intersection Collision Warning

Intersection Collision Warning applications provide warnings to drivers that a collision is likely at the upcoming intersection either due to their own speed or inattention, or that of another driver.

To quantify the benefits of such a system we aimed to determine the number of accidents that could be reduced, then by using the assumptions laid out in previous sections, calculate a monetary benefit for reducing accidents.

To begin this process, the GES database was queried for specific accident data related to the application in question. For instance, all accidents that took place in curves, and were related to speed were included in this analysis.

In 2008, there were 88 fatalities, and ~37000 other injuries where this type of application may be applicable. To determine the benefit of this system an efficacy rate must be determined to see how much of a reduction from these figures can be expected.

Through another literature review, several reports were found discussing how effective intersection collision warnings could be. The two reports and results are summarized briefly below:

- Field & Driving Simulator Validations of System for Warning Potential Victims of Red-Light Violators (Inman, Vaughan TRB 2006) – A Field and Simulation study that tested participants in a driving simulator and on a closed track. In the simulator, 90% stopped or avoided the collision, while on the track, 64% stopped or avoided the collision.
- Intersection Collision Avoidance Study (FHWA Office of Safety 2003) – An in depth analysis of literature and operational concepts of specific ICAS systems, and they state that 100% reduction in accidents is not unrealistic, however a more conservative estimate would be a 50% reduction in accidents.

Using these sources as references, we chose to use 50% accident reduction as a mid-level efficacy rate. A low level would be 25% while a high efficacy level would be 75%.

With all of this data, a discounted yearly monetary benefit can be calculated. The equation would as follows:

$$B = (EffRate_j * Adopt_n * \sum (InuryCount_{i,n} * Injury\%_i * FatalityWorth)) / DiscountFactor_n$$

Where B is monetary benefits, n is the year, j is the application, and i is the injury level (fatal, serious, etc.).

Using this formula and the low efficacy rate, preliminary benefits of ~$33 Billion were estimated.

5. Left Turn Assistant

Left Turn Assistants provide drivers information about oncoming traffic when trying to take a left-hand turn at an unprotected intersection.

To quantify the benefits of such a system we aimed to determine the number of accidents that could be reduced, then by using the assumptions laid out in previous sections, calculate a monetary benefit for reducing accidents.

To begin this process, the GES database was queried for specific accident data related to the application in question. For instance, all accidents that took place in curves, and were related to speed were included in this analysis.

In 2008, there were 26 fatalities, and ~24000 other injuries where this type of application may be applicable. To determine the benefit of this system an efficacy rate must be determined to see how much of a reduction from these figures can be expected.

Since the application is very similar to that of intersection collision warnings, the literature used to determine an efficacy rate for that application were leveraged for this application as well.

Using these sources as references, we chose to use 50% accident reduction as a mid-level efficacy rate. A low level would be 25% while a high efficacy level would be 75%.

With all of this data, a discounted yearly monetary benefit can be calculated. The equation would as follows:

$$B = (EffRate_j * Adopt_n * \sum (InuryCount_{i,n} * Injury\%_i * FatalityWorth)) / DiscountFactor_n$$

Where B is monetary benefits, n is the year, j is the application, and i is the injury level (fatal, serious, etc.).

Using this formula and the low efficacy rate, preliminary benefits of ~$21 Billion were estimated.

6. Stop Sign Movement Assistant

Stop Sign Movement Assistants alert vehicles about to cross an intersection, after stopping, of cross traffic.

To quantify the benefits of such a system we aimed to determine the number of accidents that could be reduced, then by using the assumptions laid out in previous sections, calculate a monetary benefit for reducing accidents.

To begin this process, the GES database was queried for specific accident data related to the application in question. For instance, all accidents that took place in curves, and were related to speed were included in this analysis.

In 2008, there were 110 fatalities, and ~10000 other injuries where this type of application may be applicable. To determine the benefit of this system an efficacy rate must be determined to see how much of a reduction from these figures can be expected.

Since the application is very similar to that of intersection collision warnings, the literature used to determine an efficacy rate for that application were leveraged for this application as well.

Using these sources as references, we chose to use 50% accident reduction as a mid-level efficacy rate. A low level would be 25% while a high efficacy level would be 75%.

With all of this data, a discounted yearly monetary benefit can be calculated. The equation would as follows:

$$B = (EffRate_{j} * Adopt_{n} * \sum (InuryCount_{i,n} * Injury\%_{i} * FatalityWorth)) / DiscountFactor_{n}$$

Where B is monetary benefits, n is the year, j is the application, and i is the injury level (fatal, serious, etc.).

Using this formula and the low efficacy rate, preliminary benefits of ~$10 Billion were estimated.

7. Highway/Rail Collision Warning

Highway/Rail Collision warnings provide alerts to reduce the likelihood of a collision between vehicles and trains on intersecting paths.

To quantify the benefits of such a system we aimed to determine the number of accidents that could be reduced, then by using the assumptions laid out in previous sections, calculate a monetary benefit for reducing accidents.

To begin this process, the GES database was queried for specific accident data related to the application in question. For instance, all accidents that took place in curves, and were related to speed were included in this analysis.

In 2008, there were 0 fatalities, and ~0 other injuries where this type of application may be applicable. To determine the benefit of this system an efficacy rate must be determined to see how much of a reduction from these figures can be expected.

Through another literature review, a report was found discussing how effective Highway/Rail Crossing Warnings could be. The report and results are summarized briefly below:

- Second Train Coming Warning Sign Demonstration Projects (TCRP Research Results Digest, 2002) – A demonstration study of two sites, one in Baltimore and the other in LA, where warnings were placed for approaching trains. 26% of drivers reduced the most risky behavior.

Using these sources as references, we chose to use 25% accident reduction as a mid-level efficacy rate. A low level would be 10% while a high efficacy level would be 50%.

With all of this data, a discounted yearly monetary benefit can be calculated. The equation would as follows:

$$B = (EffRate_{j} * Adopt_{n} * \sum (InuryCount_{i,n} * Injury\%_{i} * FatalityWorth)) / DiscountFactor_{n}$$

Where B is monetary benefits, n is the year, j is the application, and i is the injury level (fatal, serious, etc.).

Using this formula and the low efficacy rate, preliminary benefits of ~$0 Billion were estimated.

D. Mobility Applications

As part of the mobility analysis, two applications are analyzed: Intelligent traffic flow control and free flow tolling. Both of these applications are focused on reducing delay. Both those applications require lane-level positioning accuracy to operate and therefore would benefit from a C-HALO nationwide deployment.

1. Intelligent Traffic Flow Controls (ITFC)

ITFC uses real-time data to adjust signal phases to an optimal level. These applications could also include Green Light Optimal Speed Advisory, which would provide the subject vehicle with the optimal speed given signal phase timing at upcoming intersections.

To quantify the benefits of such a system two additional pieces of information are needed to complete the calculation. The first is to determine how much delay is currently realized at signalized intersections. This was done through a literature review, and Temporary Losses of Highway Capacity and Impacts on Performance (Phase 2), written by Oak Ridge National Laboratory for the Department of Energy, discusses sub-optimal signal timing specifically. Through surveying and significant quantitative modeling they determine that there is, as of 1999, ~295 million hours of delay at signalized intersections.

Lastly, the efficacy of these new systems needs to be estimated. Through another literature review, several reports were found discussing how much more optimal signal timing assisted in reducing delay. The three reports and results are summarized briefly below:

- Preliminary Evaluation Study of Adaptive Traffic Control System (LA DOT 2001) – Empirical study in LA with 375 intersections, reduced delay by ~21%
- Realizing Benefits of Adaptive Signal Control at an Isolated Intersection (Park and Change 2002) – A simulation study on a hypothetical intersection of two one-way streets. Reductions in delay were between 18-20%
- ITS Benefits: The Case for Traffic Signal Control Systems (Skabardonis 2001) – Empirical study of multiple California implemented systems, reductions of delay close to 25%.

Using these sources as references, we chose to use 15% delay reduction as a conservative efficacy rate.

With all of this data, a discounted yearly monetary benefit can be calculated. The equation would as follows:

$$B_n = (EffRate * Adopt_n * TotDel_n * TVoM) / DiscountFactor_n$$

Where B is monetary benefits, n is the year, and TVoM is the monetary value of time.

Using this formula, preliminary benefits of ~$10 Billion were estimated.

2. Free Flow Tolling

Toll collection without toll plazas reducing stop and go traffic surrounding current toll plazas, also beneficial, but not included in this analysis is the fact that in tolling situations, costs are actually saved by not having to build facilities. In this exercise we only look at reduced delay.

To calculate the delay reduced by free tolling systems, some metrics needed to be deciphered. Average delay at a toll facility, the total revenue of all tolling facilities, and the average toll for toll roads in the U.S is three metrics needed to calculate total delay due to toll facilities. Again, this was done through a literature review, and Temporary Losses of Highway Capacity and Impacts on Performance (Phase 2), written by Oak Ridge National Laboratory for the Department of Energy, discusses average toll delay. Through thorough quantitative analysis, they determine the average tolling delay to be 11.9 sec per vehicle.

With this figure, only the number of vehicles would be necessary to determine overall delay. To determine the number of vehicles using toll facilities, total tolling revenues and average toll were sought. In the Highway Statistics 2007 published by the FHWA, the total revenues of toll facilities was $7.7 billion, while in the Toll Facilities in the U.S. August 2009, the average toll is calculated to be $3.89 (25). Using these two figures, an annual vehicle count of ~2 billion was determined. This was grown on a year-to-year basis at a rate of 1.65% (26).

Lastly, the efficacy of these new systems needs to be estimated. Through another literature review, several reports were found discussing how much free tolling systems reducing delay. The two reports and results are summarized briefly below:

- Evaluation of Impacts from Deployment of an Open Road Tolling Concept for a Mainline Toll Plaza (Klodzinski 2007) – Twenty-month empirical study done around UCF which reduced delays by approximately 50 percent.
- Operational and Traffic Benefits of E-Zpass to the New Jersey Turnpike (NJ Turnpike Authority 2001) – EZ-pass empirical study that showed 85 percent reductions in delay.

Using these sources as references, we chose to use 70% delay reduction as a conservative efficacy rate.

With all of this data, a discounted yearly monetary benefit can be calculated. The equation would as follows:

$$B_n = (EffRate * Adopt_n * TotVeh_n * AvgDel * TVoM) / DiscountFactor_n$$

Where B is monetary benefits, n is the year, and TVoM is the monetary value of time.

Using this formula, preliminary benefits of ~$0.6 Billion were estimated.

E. Efficacy Literature Caveat

The ITS application benefit numbers are from the RITA ITS Benefits database online. Since ITS funding is part of RITA's budget, we have found and checked benefit numbers from some of these applications in documents from m the GAO (27), RAND (28), and CBO (29). These do not challenge the assumptions made and published by RITA with respect to the analyzed applications. The RITA database is the most comprehensive.

F. Summary of Benefits

After completing all these individual analyses, the sum of these benefits ranges from $160 billion to $320 billion. This range depends on whether one uses the low-level safety application efficacy rates or the mid-level efficacy rates. This translates into 1.1 to 2.2 percent of GDP. The safety benefits in the analysis dominate, making up over 90 percent of the total benefits calculated.

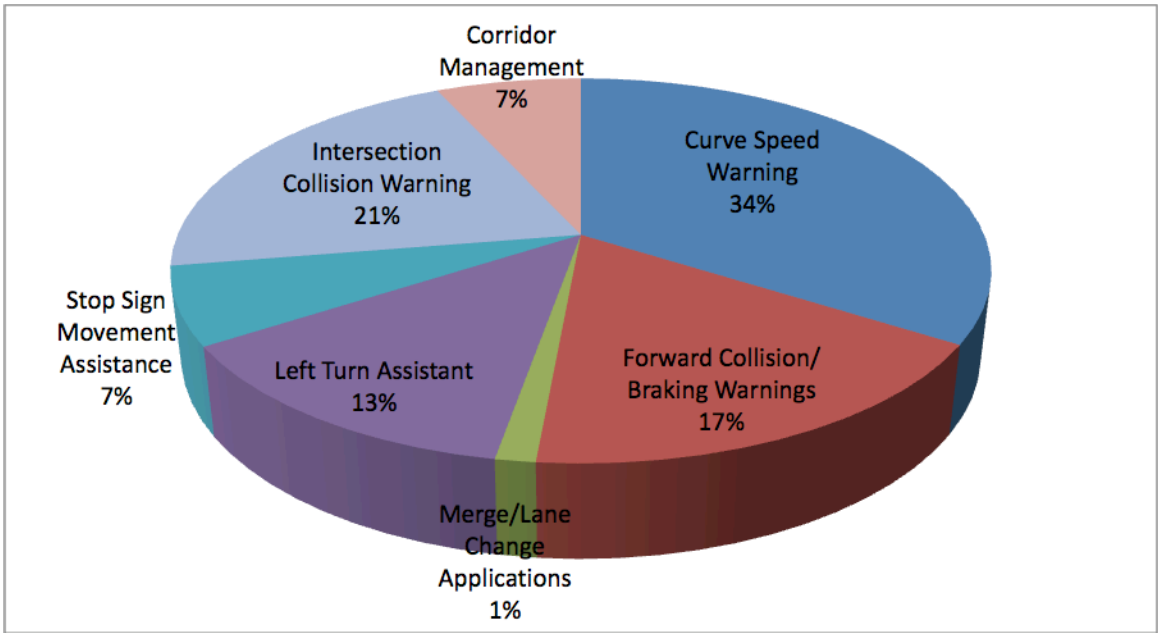

Figure 5 Benefits by Category

V. Separating HALO Costs into Good and Bad (Dark) GPS areas

In order to accurately estimate the cost of delivering C-HALO services in areas of need, we estimate the accuracy of existing location services on the ground and determine the area without good GPS coverage today We refer to this area as the "dark area" or the area, that may not realize HALO using N-RTK or HA-NDGPS, and to be targeted by a newer C-HALO infrastructure.

This chapter describes the methods and tools we have developed to estimate dark area. Emerging technologies such as the penetration of INS systems in vehicles could mitigate this gap. For example, we know from our prior work (30) that GPS augmented with INS can dead reckon to lane level precision for about 20 seconds if there are no sudden lane changes or turns at intersections (31,32).

Several reports exist on the causes of errors when measuring position on the ground using the GPS system (33). These reports address the theoretical values of the various types of errors. Table 4 below shows the possible values for the different errors attributed to locating objects on the ground using GPS.

Table 4 Sources of GPS Errors

Source	Effect (m)
Signal Arrival C/A	±3
Signal Arrival P(Y)	±0.3
Ionospheric effects	±5
Ephemeris errors	±2.5
Satellite clock errors	±2
Multipath distortion	±1
Tropospheric effects	±0.5
σ_R C/A	±6.7
σ_R P(Y)	±6.0

As part of this study, we set out to estimate the size of the "gap" using empirical and data modeling techniques to arrive at a more accurate assessment of GPS accuracy on the ground. Our method for doing this relies on understanding the satellite coverage and the visibility of satellites at a Point-of-Interest (POI) on the ground. When the POI is in an open space environment, the GPS receiver is capable of communicating with several satellites (6 or more) and is able to locate the POI with good accuracy (1-3m). When comparing this POI with another POI in an urban setting with several high-rise buildings, the number of satellites viewed drops significantly resulting in lower location accuracy.

Our effort rests on modeling the relation between position accuracy and number of satellites-in-view by incorporating the PDOP values, the height of buildings near the POI, and the open-space area - as represented by street widths - into the model. The method is tested on data from the city of San Francisco. We collected validation data in the San Francisco Downtown blocks highlighted in Figure 6.

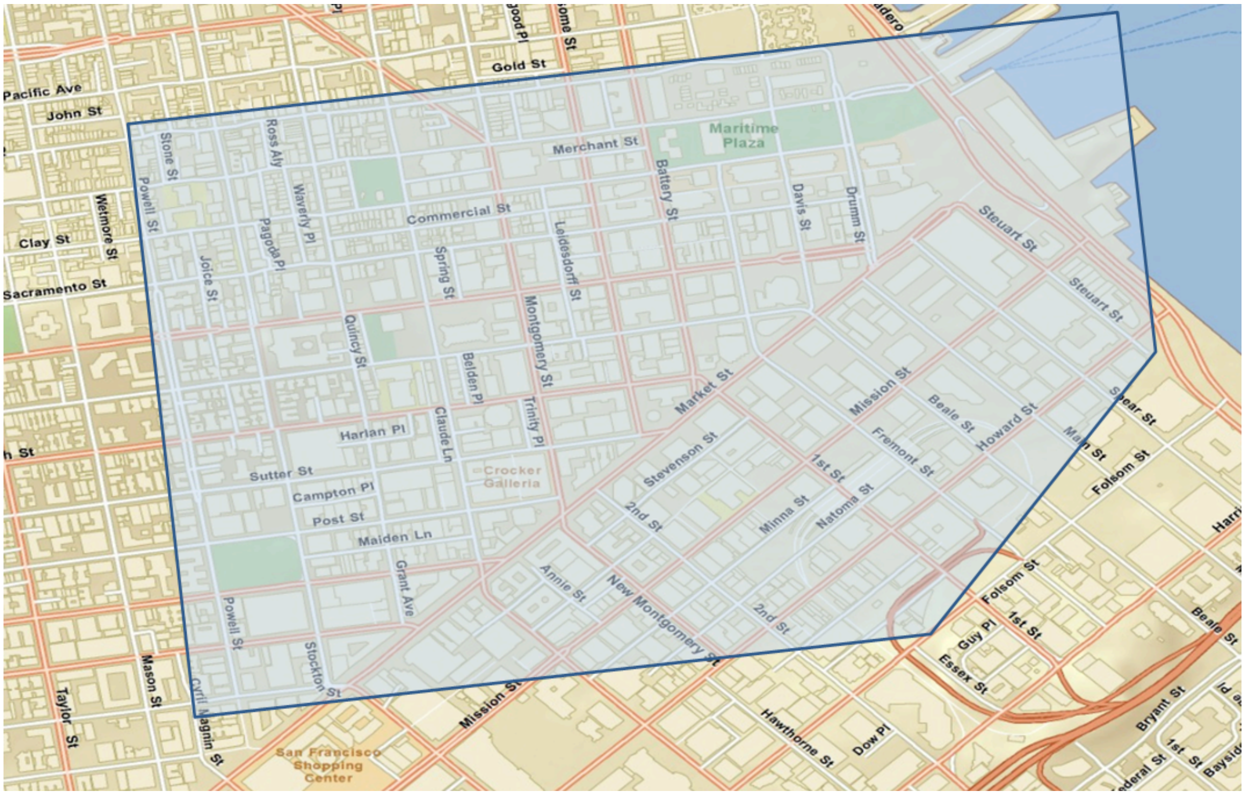

Figure 6 Shaded area represents study area

This area encompasses 2 sq.km of buildings of various heights providing us with a variety of satellite counts. Figure 7 is a Google Earth 3D rendering showing the structures in this area as of 2009.

Figure 7 3D rendering showing building coverage in validation area

A. Data for Modeling Satellite Count

In order for us to systematically replicate the modeling of the gap across various cities, we rely on data that is easily accessible in the public domain. The International Association of Assessing Officers (IAAO) in collaboration with the Urban and Regional Information Systems Association (URISA) have been among the leading efforts in enabling GIS use by cities all over the world. As a result almost all major cities in the US have implemented GIS[3] and are affiliated with either of those two organizations. In San Francisco, the assessor office manages the SFParcel GIS system which holds information on close to 198,000 parcels . Of those we were able to obtain clean data on 160,000 parcels covering approximately 86% of the built area of San Francisco. In the remaining 14%, the height data could not be verified. These are dropped from the model (visualized as grey points in the plots below). The 86% that is used covers only the parts of San Francisco that are registered with the assessor's office. This does not include open spaces, public gardens, etc. Those areas (aka Park Acres) are estimated by the San Francisco County's office to be 0.19% of the total 121sq.km area of the City of San Francisco. So for the purposes of this model, we will be assume them negligible, and the clean data we have on San Francisco from the assessor's office will be assumed to cover all the 121sq.km.

The model is constructed using the ESRI GIS software ArcMap. Data for the model includes:

- Building heights as reported by the SFParcel GIS system controlled by the County of San Francisco
- Street width as measured using the ArcMap GIS software

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[3] According to a 2003 survey by Public Technology Inc (a national not-for-profit that works with local governments) 97% of cities with a population greater than 100,000 have a GIS system in place. (Public Technology Inc., "2003 Survey on the Use of GIS Technology in Local Governments," December 2003.)

Thus building heights and street width at a Point Of Interest (POI) are “known” variables in the model and could be obtained from the GIS system of most city assessor’s office. The “unknown” variable is the satellite count. To calibrate the model we measure satellite count on the ground in the proposed area. This is done by driving around with a GPS equipped Smartphone. We developed an application on the Windows Mobile 6.5 operating system and deployed it on two HTC phones, namely, the HTC Diamond and HTC Touch Pro 2. The application logs the following values:

- GPS Longitude and Latitude
- Number of Satellites Visible
- Number of Satellites Connected
- Vertical Dilution of Position (VDOP)
- Horizontal Dilution of Position (HDOP)

The preliminary data collected is visualized in Figure 8.

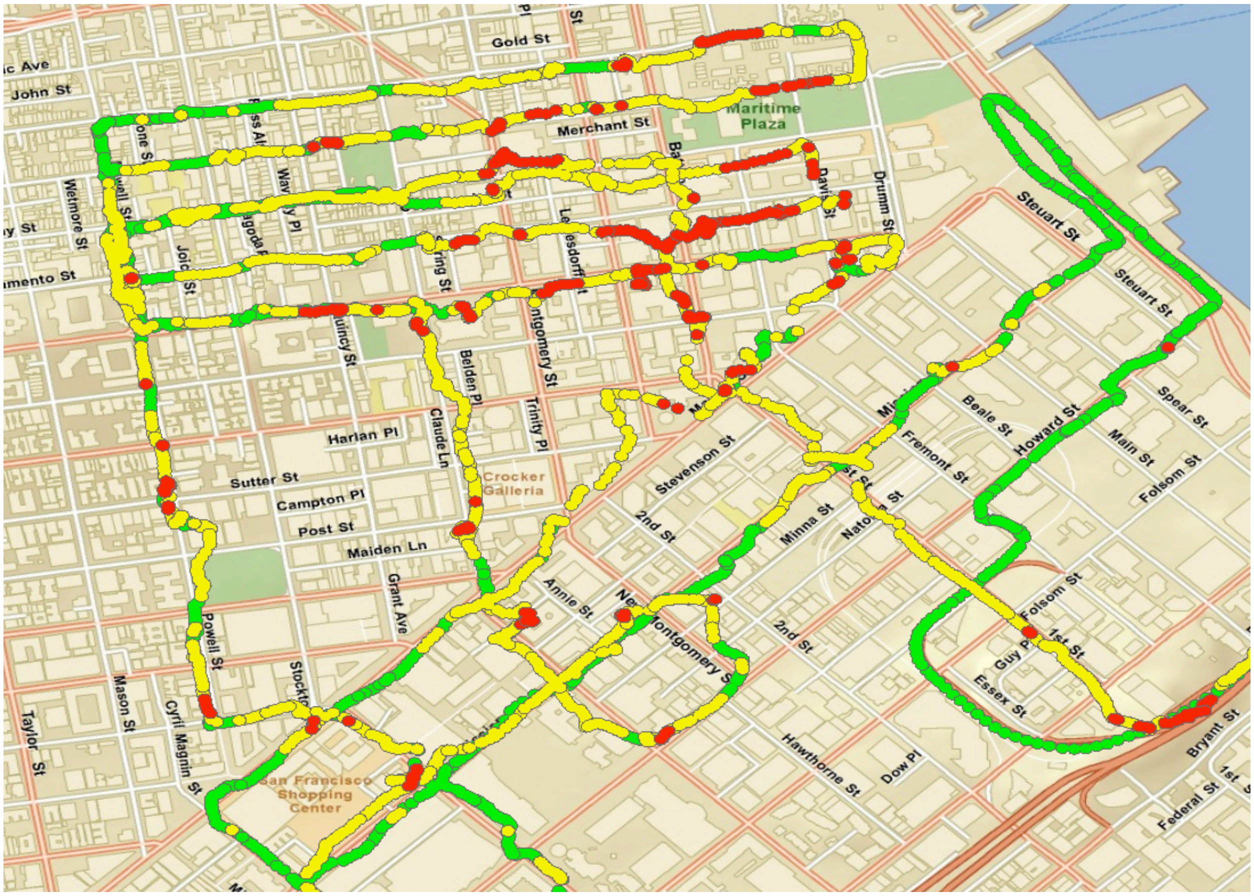

Figure 8 GPS data collection depicting satellite counts: >6 are shown in green, between 4 and 6 are shown in yellow, <4 are shown in red

The number of satellites at a POI can be taken as an indicator of the GPS accuracy. However the Horizontal Dilution of Precision (HDOP) is a better indicator of the localization accuracy of the GPS. For example, given a fixed number of satellites, the accuracy is better at a POI where the satellites are seen well spread out as compared to a place where the satellites are more clustered together. The HDOP captures this. Given the total number of operational satellites (N = 30 (57)) and the predicted number of satellites (s) at a POI, the HDOP can be theoretically calculated as follows

$$\mathrm{HDOP} = \frac{4}{s\left(1 - \frac{\sin(2\cos^{-1}(1-\frac{2s}{N}))}{2\cos^{-1}(1-\frac{2s}{N})}\right)}$$

Figure 9 shows the theoretical and the empirical HDOP values obtained from the data set along with the 95% confidence intervals for the empirical HDOP. The empirical HDOP values were obtained from the data set collected in the city of San Francisco. The theoretical HDOP is obtained from the equation above.

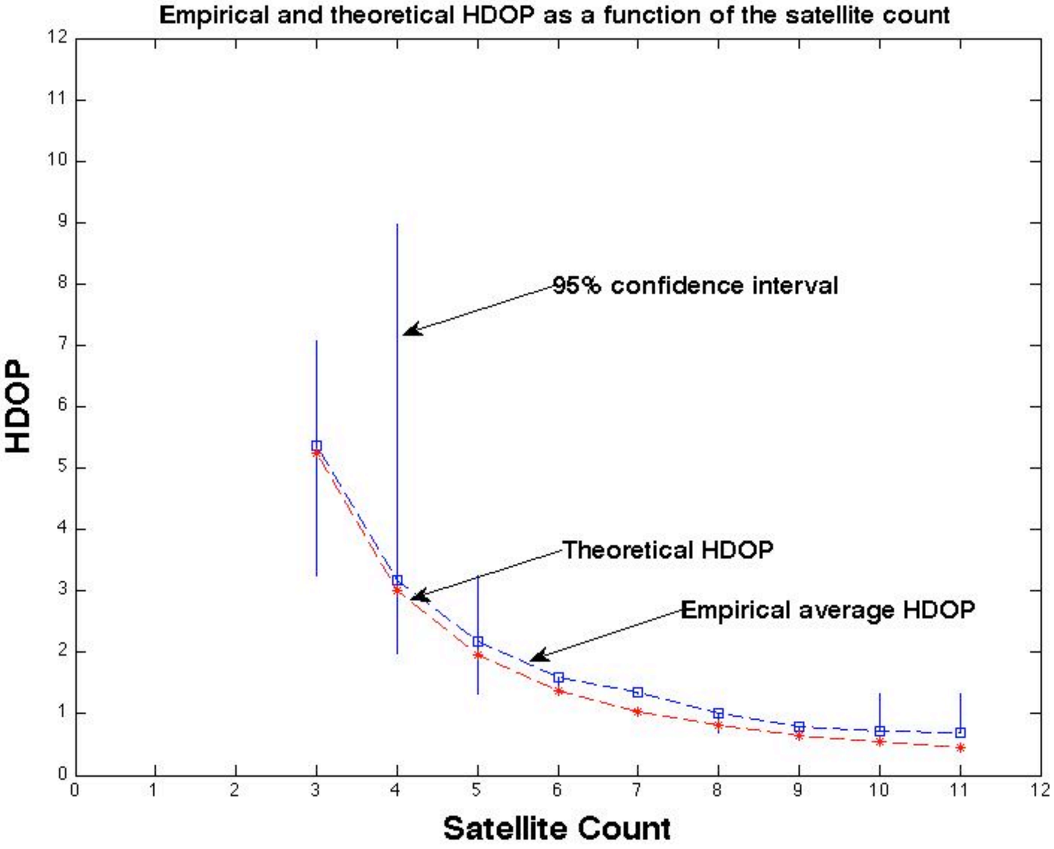

Figure 9 Empirical and predicted HDOP values with 95% confidence intervals.

The question of what values of HDOP is good for high-accuracy localization would depend on the receiver, ionospheric conditions etc. Typically, under normal conditions, HDOP values below 4 are considered to be good (52). However, for high accuracy applications, we would require the HDOP values to be lesser than 2 or 1. Using this as a rule of thumb, based on Figure 9, we roughly categorized the satellite counts as < 4, 4 to 6 and > 6 and the model predictions were carried out for these three categories. The use of 6 as a threshold for good GPS coverage is empirically supported by a 100 miles of driving data (30). In the next section we will describe the models used to predict the satellite counts and evaluate the performance based on the collected data.

B. Hidden Markov Model to Predict Satellite Counts

This section describes the method used to predict the number of satellites at a POI given the GIS data i.e. building heights and street widths. The quantity being predicted is illustrated by Figure 10.

The estimate of the satellite count at the point of interest is obtained as follows. We think of the satellites as being placed on the surface of a hemisphere with a radius R centered at the POI. We assume the POI is occluded from the satellites only by buildings at the sides of the street and there is visibility in the forward and backward directions as in Figure 10. The mask angle alpha (shown in Figure 10) is calculated based on the heights of the buildings and street width as follows.

$$\begin{aligned} \alpha &= \tan^{-1}\left(\frac{h_1}{w}\right) + \tan^{-1}\left(\frac{h_2}{w}\right) \\ \alpha &= \text{mask angle} \\ h_1, h_2 &= \text{height of building} \\ w &= \text{street width} \end{aligned}$$

Figure 10 Mask-Angle Representation using street width and building heights

The satellites visible at this point, are essentially the ones lying on a strip of the hemisphere with angular width alpha. The fraction of these satellites is given by

$$\text{Satellite Count} = \text{N} \times \alpha$$

where N is the total number of satellites in orbit. The satellite count data collected in downtown San Francisco is compared against the predicted count computed as described above. The data set consisted of 1657 data points. These were a subset of the 13822 data points collected overall. The subset was chosen by excluding data points that were not part of downtown San Francisco as in Figure 8 and data points that did not have corresponding meaningful building heights in the SFParcel GIS system. Out of these 1657 data points, 34 data points had satellite counts < 4, 568 points had satellite counts 4 to 6 and the rest had satellite counts > 6.

Table 5 shows the prediction accuracy of the model. Each column in this table is the prediction accuracy for the corresponding category of satellites. For example column 1 shows the percentage of data points having < 4 satellites being predicted as < 4, 4 to 6 and > 6 number of satellites.

Table 5 Model Prediction Accuracy

Satellites	**True < 4**	**True 4 to 6**	**True >6**
Predicted < 4	0.74	0.16	0.02
Predicted 4 to 6	0.24	0.25	0.07
Predicted > 6	0.02	0.59	0.91

The overall prediction accuracy is around 69%. The prediction accuracy is calculated by adding the fraction of data points in each of the categories multiplied with the corresponding diagonal entry. We next add a Hidden Markov Model (HMM) (51) to improve the prediction accuracies. The HMM captures the statistical dependence of the satellite count at a POI on the building heights at neighboring points as well.

The idea of the HMM modeling is as follows. Depending on the time of day, climatic conditions, or scatter in the environment, the number of satellites visible at a point could vary significantly. These random parameters lead to a stochastic dependence between the building heights and the number of satellites at a given point. Furthermore, the number of satellites at a particular point would be dependent on the number of satellites in nearby points. These dependencies could be captured by a HMM as shown in the figure below.

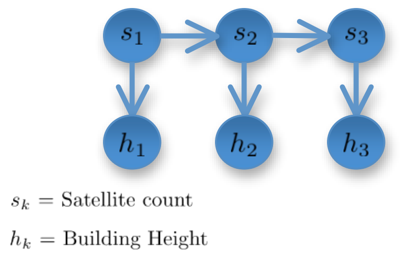

Figure 11 HMM for predicting satellite count

The nodes corresponding to the heights are values that are known. The nodes corresponding to the satellite count are the hidden nodes that need to be estimated. The hidden nodes are connected to their neighbors to model the dependency between satellite counts in adjacent regions. The transition probabilities between the satellite count variables are modeled using a sticky Markov chain (51). This is validated using the empirical data collected. The distribution of the building height given the satellite count is modeled as a Gaussian random variable with mean and variance empirically determined from the collected data. The mean height and variance for the Gaussian model and the transition probabilities between the states were obtained empirically from the collected data. 95% confidence intervals were calculated for the estimated parameters of the model. The satellite counts were predicted by taking the mean of the estimated parameters and the corresponding prediction accuracies for this model are as shown in Table 6.

Table 6 HMM Satellite Count Accuracies

Satellites	**True < 4**	**True 4 to 6**	**True >6**
Predicted < 4	0.70	0.01	0
Predicted 4 to 6	0.08	0.41	0.11
Predicted > 6	0.22	0.58	0.89

The results of this model are 87% accurate. Experimental results [53] have shown that with less than 7 satellites, GPS estimates have errors of the order of 1 meter. Therefore we focus on a 7 satellite threshold. Our model predicts that 0.3 to 4 % of the streets of San Francisco has satellite coverage of less than 7 satellites with 95% confidence. The prediction is made for all the streets of San Francisco where we have the building height data from the assessor's office. Figure 12 shows the results of the model. The figure is drawn by aggregating and averaging the values of the model into 10m x 10m grids that lie on roads. Each grid is given a color based on the average satellite count in that grid: red if <4, yellow if between 4 and 6 and green if >6. The 14% of San Francisco for which we do not have height data is not modeled. It appears as grey areas in the figure. We would also like to note that the effects of multipath are not taken into account in this modeling. Thus the green areas do not

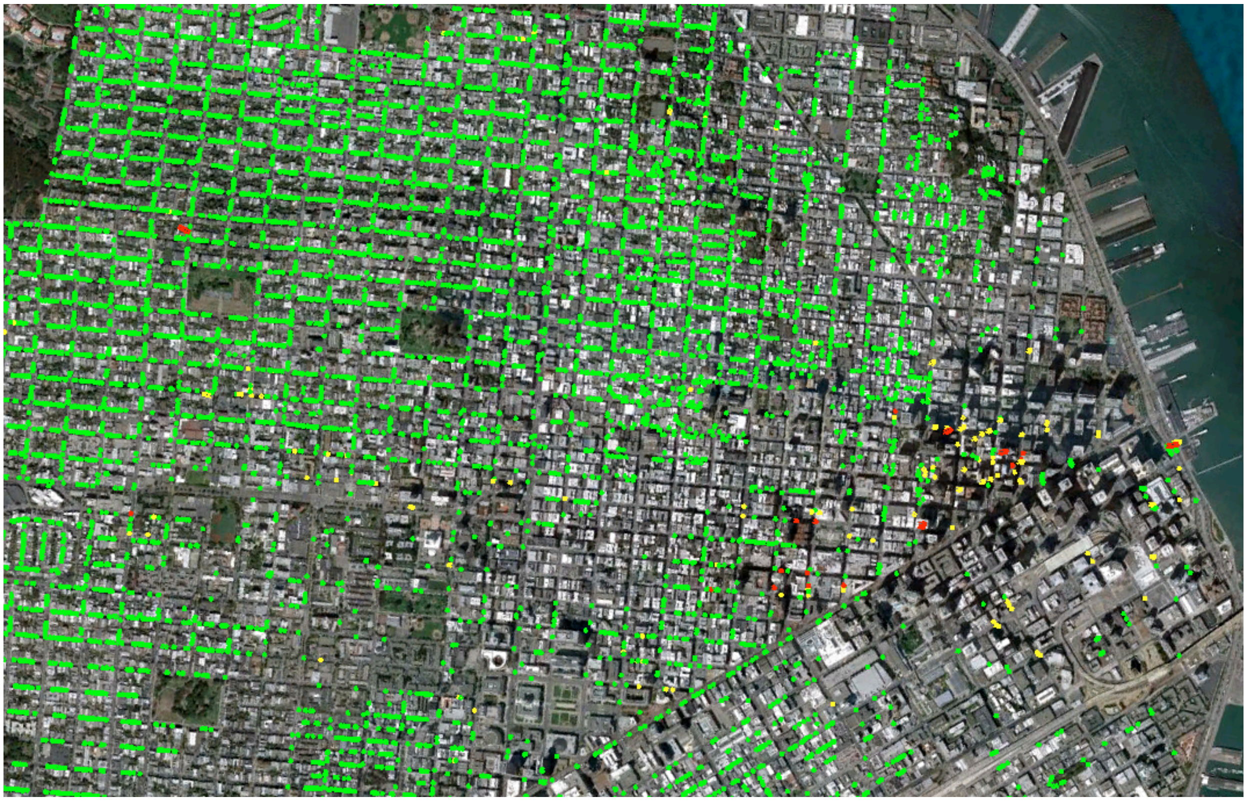

Figure 12 GPS data estimating satellite counts: >6 or more are shown in green, between 4 and 6 are shown in yellow, <4 are shown in red

necessarily reflect regions of high accuracy. Even though there is a satellite visibility of >6, multipath can cause significant errors. However, we can say with high confidence that the dark areas are regions of bad location accuracies. Table 6 can be related to some numbers in the literature. The methods in the literature use precise LiDAR data to yield good prediction accuracies [58]. The authors of [58] evaluated their method by two test cases. With a 5m RADAR digital surface map, the mean error in the predicted number of satellites using their model is 2.7 and 4.85 satellites with the corresponding error percentages being 46% and 82% in the two test cases. This improves with a more precise digital surface map. However it would be very expensive to obtain precise LiDAR data for an entire city and all the cities in the US. Under the same error metric, the mean error in the predicted number of satellites using our model is 1.85 satellites and the error percentage is 29.14%, which seems good. We use only building height data that can be obtained from the city planning department or a similar agency. However the comparison of the models is to be taken with caution given that the test data under consideration is vastly different for the two approaches. Our accuracies could be improved by having more data points. Extensive data collection during different times of the day and in different regions can help build and evaluate better models.

C. Use of the Model

The approach we adopted to obtain the satellite count on the surface in San Francisco can be repeated to any city in the US. The method is based on a GIS model constructed from the building heights and street width of the whole city – information easily accessible for all urban centers in the US via the local assessor's office. This would quantify the area where decimeter level accuracy cannot be achieved today with the current GPS and DGPS technology in many cities nationwide.

Our method produces a figure such as figure 12. Such a figure can guide the phased deployment of C-HALO infrastructure and provide insight into the full extent of new infrastructure required. The red areas are candidates for a first phase C-HALO deployment. Fortunately, they are also few in number, suggesting one might reap considerable improvements in location accuracies for moderate initial investment.

The benefits of deploying in red or yellow areas can be better understood by using GIS tools to overlay other statistics such as the distribution of accidents on figure 12. We have done this for San Francisco. Figure 13 shows a quadrant of San Francisco which include 1000m x 1000m grids of 2008 accident data as reported by NHTSA where red are areas of high accident counts, yellow those of medium counts and green of low or no accidents. This type of plot could be repeated by overlaying emissions data, or congestion data or other types of data relevant to the benefit measures guiding C-HALO pilot deployments or initial infrastructure investments.

Figure 13 Overlay of accident data on satellite count projection data

VI. Cost Assessment in Good GPS Areas

This chapter quantifies the new infrastructure investment required to realize a C-HALO service in areas with good GPS coverage based on N-RTK technology. This cost does not include the wireless communication technology between vehicles, but just the cost of deploying the infrastructure to provide the service. For the purposes of this analysis we explored the cost of implementing N-RTK infrastructure. This of course, is an upper bound on the cost estimate of the infrastructure since in reality some areas of the U.S. are already covered by N-RTK service, while others areas may not need it (i.e. some areas may already have C-HALO capability without N-RTK).

The present N-RTK system consists of a set of references stations and servers installed and maintained by companies/governmental agencies offering the service. Customers use the service by paying a subscription fee. The NRTK servers provide the rovers with the RTCM corrections as and when requested by the rover. A typical N-RTK system as implemented by companies like Trimble and adopted by the present DoT's, consists of the following components[4]:

1. N-RTK base stations with geodetic and communication capabilities
2. Server(s) that handle incoming NRTK requests and RTK corrections, process the data and transmits the correction data to the rovers.
3. Communication links between reference stations and server(s) and the rovers and the server(s).

The capital costs involved in setting up such a system would include

a) Hardware - NRTK reference stations (*) and the servers.
b) Software on the servers and reference stations. This should also have the ability to handle secure communication.
c) Design (hardware, site selection etc), testing and installation of the reference stations (*).
d) Predicted hardware and software upgrades (*).

Variable costs include

a) Hardware and software maintenance costs for the server and reference stations (*)
b) Rent/value of facility for the reference stations (*) and servers
c) Link costs for the communication from reference stations to server (*) and from server to rovers
d) Power supply to reference stations (*) and servers.
e) Customer support

The cost estimates in Table 7 are for the installation and maintenance of a single base station and include the costs marked (*) in the NRTK system components.

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[4] The OSI National NRTK solution, http://www.fig.net/pub/athens/papers/ts11/TS11_5_Bray_Greenway.pdf

A. N-RTK Base Station Cost Estimation

To begin estimating the infrastructure cost of deploying N-RTK infrastructure, discussions, via email and phone, were held with employees of three current N-RTK deployments, 2 state DOT's (Iowa [Steve Milligan] and Ohio [Dave Beiter) and one Cooperative (Washington [Gavin Schrock]). During these emails and conversations the costs associated with infrastructure cost requirements, as well as maintenance and operating costs were focused on (47,48,49,60). We also obtained concrete documents on invoices and cost reports for the hardware, servers, services etc (69,70) from these DOT's. These costs are summed and determined over the 22-year horizon using a 5% discount rate. The calculations are as follows.

Table 7 N-RTK Cost Estimation (No Other (Contingency) Costs) (47,48,49.60)

	Cost Estimate (Per Base Station)
Hardware	**$20,000**
Software	$400
R&D	$300
IT	$120
Misc Hardware	$120
Servers	$90
Support/Maint	$1,000
Comm/Power	$1,000
Rent	$24,000
Other	$0
TOTAL per Tower	**$47,030**
PV of Horizon Cost	**$413,402**

This is the representative cost given average levels of all the above costs. There are low and high estimates for each cost category, including the useful life of the hardware, which ranges from 7 to 15 years. This useful life changes the 22-year horizon cost of the hardware.

The range of infrastructure costs is from $220K to $615K per base station for the life of the system. Using a range of annual contingency expenses from $25K to $70K the range of infrastructure costs increases to $570K to $1.6M per base station for the life of the system. If one were to provide N-RTK coverage over the entire US land mass for the horizon of this project, approximately 2,730 base stations would be needed. Using this figure, nationwide N-RTK coverage would cost between $1.6B to $4.4B. This may be compared to benefits ranging between $160 and $300 billion from the Intelligent Transportation Systems Sector alone.

VII. Further Research

While accomplishing many things during this process, there are still many areas of research that could improve the analysis and enhance scope to incorporate more levels of detail. Areas of further explorations are briefly discussed below:

- **Further model refinement:**
  Continue to update the model with more empirical data and expand use to other cities and use nationwide to determine nationwide 'dark area.' Different models than the HMM could be investigated for better accuracy. Obtaining real data that spans across weather conditions and time would enable the model to provide time-based projection of satellite coverage, yielding a statement such as satellite count less than 6 for x % of the time. The use of variations on the satellite count, such as number of satellites used to calculate position could offer a better understanding of multi-path errors in the region.
- **Cost of infrastructure adjustment:**
  Utilizing the new 'dark area' estimation a more accurate infrastructure cost estimate can be made based on average coverage area of a base station.
- **Communication Technology Research:**
  Further research needs to be done on how the actual augmentation services will be communicated to the vehicles and between vehicles. This analysis has not been included in this report, but is integral in realizing the benefits of the new ITS applications.
- **Benefit Refinement:**
  Ultimately, the benefits calculations could be expanded to include environmental benefits.
- **Technology Assessment:**
  To achieve a more thorough understanding of where N-RTK stands in terms of cost effectiveness a more complete technology assessment needs to be completed. As part of this, the cost of infrastructure for each technological alternative needs to be completed, as well as analyzing the capabilities of each technology. Once this analysis is complete, the technologies can be compared and a prudent decision going forward could be made.
- **Other Economic Stimulus:**
  Analysis could be completed on what type of economic development may be induced due to these applications, specifically the mobility applications since the main component of the benefits is saved time. Typically if users are saving time, they are using that time to create benefits in another industry or realm. These effects need to be explored more fully to get a better estimate of the full benefits of implementing C-HALO services.

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Appendix A – Market Presence (X-Major; O-Minor)

	Aero.	Agri.	AV	Constr.	Def.	Mari.	Mine	Survey
Automated Positioning Systems							X	
Atair Aerospace					X			
Axio-Net GmbH	O	O		O		O		O
Biscarosse BV					X			
C&C Technologies						X		
Credent Technologies	X							
Crossbow Technology	O	O		O	O	O	O	O
DataGrid Inc.	O	O		O		O	O	X
Fugro/Omnistar	X	O	O	X		X	X	X
GeoKosmos	X							
GPS Ag		X						
Grumman			X		X			
Hemisphere GPS		X				O	O	O
Honeywell					X			
Javad GNSS				X				X
John Deere/Navcom Technology	X			O				
Leica Geosystems/ Novatel/Hexagon	O	X		X			O	X
Locata Corporation		O		X			X	
Magellan								X
MMIST Inc.					X			
NavSys Corportation	X	O	X	O			O	
Novariant	O	X		O	O		X	
New Zealand Aerial Mapping	X							
Septentrio BV	X					X		
Stara Technologies, Inc.					X			
Subsea 7/Veripos						X	X	X
Suzhou FOIF				X				X
TopCon/Sokkia	O	X		X		O	X	X
Trimble	O	X	O	X	O	X	X	X

Appendix B – Process of Selecting ITS Application that Stand to Benefit from C-HALO

A. Initial Application Selection Matrix (1,2)

ITS Applications	**Safety**	**Location Services Necessary**	**Accuracy Requirements**	**Transmission**	**Min Frequency**	**Allowable Latency**	**Required Range**
Units	**(Y/N)**	**(Y/N)**	**(m)**	**(Event/Periodic)**	**(Hz)**	**(msec)**	**(m)**
Traffic Signal Violation Warning*	Y	Y	1	P	10	100	250
Stop Sign Violation Warning	Y	Y	1	P	10	100	250
Curve Speed Warning*	Y	Y	1	P	1	1000	200
Emergency Electronic Brake Lights*	Y	Y	1	E	10	100	300
Adv. Warning Info/Weather & Road Conditions							
Approaching Emergency Vehicle Warning	Y	Y	5	E	1	1000	1000
Emergency Vehicle Signal Preemption	Y	Y	5	E	N/A	1000	1000
SOS Services	Y	Y	25	E	1	1000	400
Post-Crash Warning	Y	Y	1	E	1	500	300
In-Vehicle Signage	Y	Y	5	P	1	1000	200
Work Zone Warning	Y	N	N/A	P	1	1000	300
In-Vehicle Amber Alert	Y	N	N/A	E	1	1000	250
Safety Recall Notice	Y	N	N/A	E	N/A	5000	400
JIT Repair Notification	N	N	N/A	E	N/A	N/A	400
Low Parking Structure Warning	Y	Y	5	P	1	1000	100

ITS Applications	Safety	Location Services Necessary	Accuracy Requirements	Transmission	Min Frequency	Allowable Latency	Required Range
Units	**(Y/N)**	**(Y/N)**	**(m)**	**(Event/Periodic)**	**(Hz)**	**(msec)**	**(m)**
Wrong Way Driver Warning	Y	Y	1	P	10	100	500
Low Bridge Warning	Y	Y	5	P	1	1000	300
V2V Road Feature Notification	Y	Y	5	E	2	500	400
Cooperative Glare Reducation	N	Y	1	P	1	1000	400
Instant Messanging	N	N	N/A	E	N/A	1000	50
Vehicle-Based Road Condition Warning	Y	Y	25	E	2	500	400
Visibility Enhancer	Y	Y	1	P	2	100	300
Road Condition Warning	Y	N	N/A	E	1	1000	200
Highway Merge Applications							
Highway Merge Assistant	Y	N	N/A	P	10	100	250
Intelligent On-Ramp Metering	N	N	N/A	E	1	1000	100
Blind Merge Warning	Y	N	N/A	P	10	100	200
Left Turn Assistant*	Y	Y	1	P	10	100	300
Stop Sign Movement Assistance*	Y	Y	1	P	10	100	300
Pedestrian Crossing Information	Y	Y	1	P	10	100	200
Collision Warning Applications							
Pre-Crash Sensing*	Y	Y	1	E	50	20	50
Cooperative Forward Collision Warning*	Y	Y	1	P	10	100	150

ITS Applications	Safety	Location Services Necessary	Accuracy Requirements	Transmission	Min Frequency	Allowable Latency	Required Range
Units	**(Y/N)**	**(Y/N)**	**(m)**	**(Event/Periodic)**	**(Hz)**	**(msec)**	**(m)**
Cooperative Collision Warning	Y	Y	1	P	10	100	150
Highway/Rail Collision Warning	Y	Y	1	E/P	1	1000	300
Intersection Collision Warning	Y	Y	1	P	10	100	300
Adapative Headlight Aiming	Y	Y	1	P	1	1000	200
Adaptive Drivetrain Management	N	Y	5	P	1	1000	200
Lane Change Warning*	Y	Y	1	P	10	100	150
Blind Spot Warning	Y	Y	1	P	10	100	150
Corridor Management							
Cooperative Vehicle-Highway Automation System	Y	Y	5	P	50	20	100
Cooperative Adaptive Cruise Control	Y	Y	5	P	10	100	250
Intelligent Traffic Flow Control	N	Y	5	E	1	1000	250
Free-Flow Tolling	N	Y	1	E	N/A	50	50
Private Applications							
Enhanced Route Guidance & Navigation	N	Y	1	E	N/A	1000	200
Point of Interest Notification	N	Y	5	P	1	1000	400
Map Downloads & Updates	N	N	N/A	E/P	1	1000	400
GPS Correction	N	N	N/A	P	1	1000	400

B. Applications that stand to benefit from C-HALO

1. Safety

a) Curve Speed Warning

Aid drivers in negotiating curves at appropriate speeds.

b) Emergency Electronic Brake Light

Warns a driver when forward vehicle brakes hard (deceleration is above a predetermined threshold). This is very similar to Cooperative Forward Collision Warning which is used to preemptively avoid rear-end collisions with vehicles in front of the subject vehicle.

c) Highway Merge Assistant

Warns vehicles on highway on-ramps if another vehicle is occupying its merging space (or in its blind spot). This is similar to Blind Merge Warning where warnings are used for vehicles attempting to merge with limited sight distance, and another vehicles is predicted to occupy the merging space.

d) Blind Spot Warning

Warns subject driver if another vehicle is occupying his/her blind spot during an intended lane change maneuver.

e) Lane Change Warning

Warns subject driver if a lane change is likely to cause a collision. Triggered by turn signal activation.

f) Intersection Collision Warning

Provides warnings to drivers that a collision is likely at the upcoming intersection

g) Cooperative Collision Warning

Warns vehicles when a collision is likely with surrounding vehicles.

h) Left Turn Assistant

Provides drivers information about oncoming traffic when trying to take a left-hand turn at an unprotected intersection.

i) Stop Sign Movement Assistance

Warns vehicles about to cross an intersection, after stopping, of cross traffic.

j) Highway/Rail Collision Warning

Provides warnings to reduce the likelihood of a collision between vehicles and trains on intersecting paths.

k) Pedestrian Crossing Information

Alerts vehicles if there is danger of a collision with a pedestrian in a crosswalk.

2. Mobility

a) *Free Flow Tolling*

Toll collection without toll plazas reducing stop and go traffic surrounding current toll plazas.

3. Emissions

a) *Adaptive Drivetrain Management*

Allows vehicles to anticipate shift change patterns, and assist engine management systems to stabilize the transmission. Effects should be seen in increased gas mileage, reduced emissions, and improved shifting performance.

4. Mobility & Emissions

a) *Intelligent On-ramp Metering*

Uses real-time data to adjust ramp metering signal phases

b) *Intelligent Traffic Flow Control*

Use real-time data to adjust signal phases to an optimal level. Could also include Green Light Optimal Speed Advisory, which would provide the subject vehicle with the optimal speed given signal phase timing at upcoming intersections.

c) *Private Applications (Etc.)*

Enhanced Route Guidance & Navigation
Drive-thru Payments
Parking Lot Payment/Spot Locator

C. References

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Appendix C – Querying Methodology Matrix

	Driver Related Factors							Manner of Collision			Relation to Junction								Roadway Alignment		Traffic Control Device				Vehicle Manuever				
	Drowsy, Sleepy, Asleep, Fatigued	Operating in Careless or Inattentive Manner	Improper of Erratic Lane Changing	Failure to Keep in Proper Lane	Failure to Yield Right of Way	Driving Too Fast for Conditions	Driving in Excess of Posted Maximum	Front-to-Rear	All	Other	Intersection (Non-Interchange)	Intersection Related (Non-Interchange)	Rail Grade Crossing (Non-Interchange)	Crossover Related (Non-Interchange)	Intersection (Interchange Area)	Intersection Related (Interchange Area)	Crossover Related (Interchange Area)	All	Curve	All	Stop Sign	Stop Sign	Other	All	Turning Left	Changing Lanes or Merging	Negotiating a Curve	Other	All
Curve Speed Warning						X	X		X									X	X					X			X		
Electrtonic Brake Warning	X	X						X										X		X				X					X
Merge Warning (1)	X	X								X								X		X				X		X			
Merge Warning (2)			X	X					X									X		X				X		X			
Left Turn Assistant (1)					X					X	X	X		X	X	X	X			X				X	X				
Left Turn Assistant (2)	X	X							X		X	X		X	X	X	X			X				X	X				
Stop Sign Assistant	X	X								X	X	X		X	X	X	X			X	X	X						X	
Intersection Collision Warning	X	X								X	X	X		X	X	X	X			X			X					X	
Highway/Rail Collision Warning	X	X								X			X							X				X	X			X	

Appendix D – Efficacy Rate Matrix

	Low	**Mid**	**High**
Curve Speed Warning	20.00%	40.00%	70.00%
Emergency Electronic Brake Lights	10.00%	25.00%	50.00%
Highway/Rail Collision Warning	10.00%	25.00%	50.00%
Intersection Collision Warning	25.00%	50.00%	75.00%
Left Turn Assistant	25.00%	50.00%	75.00%
Merge/Lane Change Applications	15.00%	35.00%	60.00%
Stop Sign Movement Assistance	25.00%	50.00%	75.00%
Free Flow Tolling		70.00%	
Intelligent Traffic Control		15.00%	

Appendix E – Cost Estimation Emails

Email from David Beiter to Adam Goodliss:

Adam, my answers to your questions below are in Red

David J. Beiter, PE /SIT, Transportation Engineer 2
ODOT Office of Aerial Engineering and Surveying
1602 West Broad St, Columbus, Ohio 43223
Voice: (614)-275-1372 FAX: (614)-275-1673
e-mail: dave.beiter@dot.state.oh.us

Adam Goodliss <agoodliss@gmail.com>	To	<Dave.Beiter@dot.state.oh.us>
10/20/2010 11:59 AM	cc	
	Subject	Re: RTK/CORS Network Cost Information UC Berkeley Research

Dave,

Thanks so much for getting back to me. I just want to clarify what you wrote to make sure I understand you correctly, and then ask a couple questions to follow up.

From your summary, I understand the base towers cost ~$2K fully loaded (installation, crew, fixed cost, etc.) and the mount cost fully loaded, if put on a building, cost $500. This does not include the receiver or antenna.
The $2k and $500.00 cost detailed was for materials only, labor costs are not figured in

Follow up questions:

Are there any estimated maintenance costs of such a system? Are the on a per tower basis? Maintenance is a fairly low cost, the only "normal" maint items are the battery back-ups that are replaced every 2 yrs approx $150.00 / station.

Am I correct in assuming that the receiver is what is used by the end user? The end user is therefore responsible for the cost of this equipment and any data plan necessary. For the rovers, yes. Each base (CORS) has a GPS receiver and antenna, and yes the end users are required to pay for their own data plan.

What is the antenna's purpose? Are those the responsibility of the end user or the DOT? The antenna is the device that collects the GPS signal, each CORS has one. These are the responsibility of the DOT

Do you have any range of costs for receivers and antennas? I am assuming the range may be significant depending on what brand and function it is meant to serve. A high end GNSS receiver and antenna (Geodetic Grade) (Like what we have on our stations) will run around $18k

How many users are on your system currently? How long has it been operational? Is there an industry (agriculture, construction, etc.) that dominates the network? We currently have 964 users on our system. It has been operational since 2004. Our users are, in order of prevalence : Surveyors, Agricultural, GIS users, Construction machine control. Surveyors are, right now our biggest users but the Ag market has come on strong in that last few years and I expect it to be our biggest user in the near future.

Adam, if you have any further questions, or need clarification, just let me know or give me a call

Thanks
DJB

Again, thanks for the timely response. Look forward to hearing from you soon.

Cheers,
Adam

On 10/18/10 5:29 AM, "Dave.Beiter@dot.state.oh.us" <Dave.Beiter@dot.state.oh.us> wrote:

We built our Trimble VRS network completely in house, the Concrete monuments with foundations extending down at least 10' at 3' diameter cost us approximately $2000.00 each in materials, with a three man crew for 3 partial days. Our building mount stations cost about $500.00 in materials and only took us 1 day to complete with the 3 man crew. Please note that these costs do not include the receiver or antenna.

If you need anything else, let me know

Thanks
DJB

David J. Beiter, PE /SIT, VRS/CORS system Manager
ODOT Office of Aerial Engineering and Surveying
1602 West Broad St, Columbus, Ohio 43223
Voice: (614)-275-1372 FAX: (614)-275-1673
e-mail: dave.beiter@dot.state.oh.us

Adam Goodliss <agoodliss@gmail.com> 10/14/2010 07:29 PM
To Adam Goodliss <agoodliss@gmail.com>

Subject: RTK/CORS Network Cost Information - UC Berkeley Research

Hello, My name is Adam Goodliss and I am currently a graduate student, in transportation engineering, at the University of California, Berkeley. I have been working on a research project revolving around analyzing the costs and benefits of high accuracy location data with regards to intelligent transportation systems. You can find more information at this website, http://ucbchalo.wordpress.com/ <http://ucbchalo.wordpress.com/> . I have contacted you specifically due to your involvement with CORS/RTK networks. As part of our research we are looking into N-RTK solutions among others. I was wondering if you had additional cost details (most not available on your website) from an infrastructure/maintenance point of view, ie. the cost of a tower, installation cost, etc. Ultimately, I want to estimate the cost of implementing N-RTK networks of differing sizes and possibly on a national scale.

I also realize that you could have possibly worked with Trimble or Leica Geosystems so if they would be more suited to deal with this type of question please advise accordingly. If you do not have this information, but know someone within your organization that does I would greatly appreciate being put in touch with them.

Thanks in advance, and if you have additional questions please do not hesitate to be in touch via email or at 781.888.8033. -Adam

Email from Steve Milligan to Adam Goodliss:

Adam,

The Iowa network cost approximately $1.70 million, and it consists of 80 reference stations. Each reference station cost approximately $21,250 which included installation.

In the first 1.75 years of operation it cost approximately $60,000 for equipment repairs and replacements due to lightning/power surges. Software and firmware upgrades run approximately $80,000/year.

Let me know if you need any additional information.

Regards,

Steve Milligan
Statewide RTN Coordinator
515-239-1981
515-290-2831 cell

From: Adam Goodliss <agoodliss@gmail.com>
To: Milligan, Steven [DOT]
Sent: Fri Oct 15 12:21:08 2010
Subject: Re: RTK/CORS Network Cost Information - UC Berkeley Research

Steve,

Thanks for the timely response. I appreciate any information you are able to share with me.

-Adam

On 10/15/10 6:47 AM, "Milligan, Steven [DOT]" <Steven.Milligan@dot.iowa.gov> wrote:

Adam,

I'm not in the office today, but I will get this information together and send it to you.

Steve Milligan
Statewide RTN Coordinator
515-239-1981
515-290-2831 cell

From: Adam Goodliss <agoodliss@gmail.com>
To: Adam Goodliss <agoodliss@gmail.com>
Sent: Thu Oct 14 18:19:09 2010
Subject: RTK/CORS Network Cost Information - UC Berkeley Research

Hello,

My name is Adam Goodliss and I am currently a graduate student, in transportation engineering, at the University of California, Berkeley. I have been working on a research project revolving around analyzing the costs and benefits of high accuracy location data with regards to intelligent transportation systems. You can find more information at this website, http://ucbchalo.wordpress.com/.

I have contacted you specifically due to your involvement with CORS/RTK networks. As part of our research we are looking into N-RTK solutions among others. I was wondering if you had additional cost details (most not available on your website) from an infrastructure/maintenance point of view, ie. the cost of a tower, installation cost, etc. Ultimately, I want to estimate the cost of implementing N-RTK networks of differing sizes and possibly on a national scale.

I also realize that you could have possibly worked with Trimble or Leica Geosystems so if they would be more suited to deal with this type of question please advise accordingly. If you do not have this information, but know someone within your organization that does I would greatly appreciate being put in touch with them.

Thanks in advance, and if you have additional questions please do not hesitate to be in touch via email or at 781.888.8033.

-Adam