Decision Support Technology for Public Safety Resource Allocation: Location of Fire Stations in a Fiscally Constrained Environment

Amy Jo Wendholt*  
Michael P. Johnson**  
H. John Heinz III School of Public Policy and Management  
Carnegie Mellon University  
Pittsburgh, PA 15213-3890

Revised June 3, 2004

*awendhol@andrew.cmu.edu, **johnson2@andrew.cmu.edu; corresponding author
Amy Jo Wendholt is a May 2004 graduate of the Master’s of Science in Public Policy and Management program with an emphasis in Financial Management. Michael P. Johnson is Associate Professor of Management Science and Urban Affairs.
This report is based on a final report authored by Ms. Wendholt in October 2003 to satisfy requirements for the InformationWeek Fellowship. The authors thank the many City employees who generously provided valuable assistance throughout the process.
Executive Summary

The City of Pittsburgh is facing a severe financial crisis and seeks strategies to reduce expenditures while maintaining an acceptable quality of services. Currently the Bureau of Fire accounts for nearly twenty percent of the City’s expenses, and evidence from cities of similar size to Pittsburgh suggests that fire service expenditures may be one source of fiscal economies. This report represents the culmination of efforts to design and implement an information system to aid City decision makers in designing policy alternatives for fire services design. This decision support methodology generates service characteristics for existing and proposed station configurations of Bureau of Fire services in the City of Pittsburgh. Additionally, this methodology develops alternative station configurations that optimize stated goals of the decision makers.

This system methodology was developed using best practices from the disciplines of management science, information systems and policy analysis. It is not intended to provide a single recommendation regarding public safety expenditures. Instead, it provides information regarding a collection of public safety strategies that offer, in some way, an improvement over current practice. The goal of this system is to assist decision makers at the City level to identify specific service alternatives and gain deeper understanding of trade-offs between the cost, service and equity implications of these recommendations.

The results of this analysis demonstrate significant opportunities for resource savings that may not degrade service quality substantially. For example, we find that reductions of 27% in the number of engine companies and 45% in the number of truck companies in the city of Pittsburgh preserve standard measures of service quality. Results of our models are robust to alternative measures of demand for fire services and service coverage.

This study is based on quality data and reasonable modeling assumptions. However, these results should be interpreted as preliminary since this study has benefited from limited feedback from academic researchers but has not been the subject of journal-quality peer review. In addition, there are a number of modeling extensions that may generate even more realistic and accurate results. Nevertheless, we believe that our work provides a basis for informed discussions between various stakeholder groups regarding public safety expenditures.
Introduction

The City of Pittsburgh, like many cities today, is facing a severe financial crisis. As Mayor Tom Murphy states in the Fiscal Year 2003 Operating Budget, “Yearly revenues have failed to keep pace with the basic expenses of operating the City.”¹ For the past 10 years the City has battled a structural deficit in which expenditures have exceeded revenue. In fact, the Mayor and PGH 21, a panel of community leaders assembled to study the City’s finances, are estimating a deficit of over $50 million for fiscal year 2003 alone.² In this period of tightening financial belts, public safety expenditures (Bureaus of Fire and Police, Emergency Medical Services, and the Emergency Operations Center) have accounted for one third of the City’s expenses—the single largest City expenditure. In 2002 and 2003, operating costs for these services represented 39% and 37% respectively of the City’s expenditures.³ The service levels currently found in Pittsburgh have changed little from those established 50 years ago. At that time, Pittsburgh was a City of 600,000 people; today Pittsburgh’s population totals 335,000 and it continues to shrink. In addition, safety enhancements such as better building codes, fire resistant material, smoke alarms and home extinguishers have greatly reduced the incidence of fire. Other Cities have been able to “right-size” their firefighting force, reducing the number of stations and firefighters to correspond with the changing needs of the City. Last year, in a national comparison with 33 Cities in the population range of 250,000-499,999, Pittsburgh ranked first in fire staff with 896—the average in this range is 127.²⁴ According to City officials, these costs must be reigned in if Pittsburgh hopes to get its finances back on track.

The Mayor and City Council members have tried for years to reduce the expenditures of these service areas to no avail. Several studies have been performed on the City all calling for reductions in Fire Services. Despite the failures of previous years, today the City faces a unique opportunity to achieve its goals. With the threat of bankruptcy, and the corresponding dissolution of union contracts looming, the firefighters now have an incentive to engage in negotiated reductions. While the political battle necessary to begin deliberations may have been won, the difficult process of determining how and where to cut services, meeting the fiscal goals of the City while maintaining acceptable levels of coverage for Pittsburgh residents remains. Public

¹ Murphy, Tom. *City of Pittsburgh 2003 Operating Budget.*
³ Ibid.
safety is a complex policy issue, fraught with emotions, that affects all city residents. Providing high-quality public safety services in an equitable manner at minimal cost is perhaps the most fundamental problem that public managers face. This process involves the optimization of conflicting economic, social, and political goals and must be thoroughly analyzed before any successful decision can be achieved.

The *InformationWeek* fellowship provided the funding necessary to design and create an information system to aid City decision makers in navigating this challenging process. Our decision support system assists the decision making process by generating auditable data for the existing and any proposed station configurations of Bureau of Fire services in the City of Pittsburgh. Additionally, the system develops alternative station configurations based upon the stated goals of the decision makers. The system reports a wide variety of process and outcome measures including: percentage of the City covered according to both ISO (Insurance Services Office, Inc.) and NFPA (National Fire Protection Association) guidelines; percentage of the City with double and triple coverage; average response time; percentage of the City’s population, area, and housing units covered; maximum distance to a station and other measures. Moreover, the system allows users to test a variety of assumptions regarding service delivery strategies and to view associated recommendations for fire facility locations, service levels and costs.

This system was developed using best practices from the disciplines of management science, information systems and policy analysis. It is an update of the models presented in an earlier draft of the *InformationWeek* final report dated October 2003 and presented to City Council in December 2003. This model has been updated in three major ways: (1) the method for distance calculations now uses individually calculated travel times; (2) our models can now represent the triple coverage that the City of Pittsburgh requires for the service of engine trucks, and (3) coverage levels were estimated for three different levels of spatial aggregation (Census blocks, block groups and tracts).

As a result of these updates, and especially the third, we feel comfortable providing a range of recommendations regarding reductions in public safety expenditures that do not result in significant reductions in safety levels on the basis of commonly-accepted metrics. We hope that these recommendations can provide tangible guidance to policymakers and stakeholders as they discuss means to reduce local government expenditures in fire services. We also hope that this
project provides a conceptual framework for analysis related to policies to reduce local
government expenditures in other areas as well.

While the original goal of this project was to develop a “decision support system” (DSS), i.e. a
software application that would enable users to generate policy alternatives using automated
methods of data analysis and model solutions, this report describes only the building blocks of
such a system: data, models and visualization methods. Development of a true DSS is a resource-
intensive enterprise that we leave to others to pursue. In addition, while the research in this report
has been presented at a recent professional conference, and the report has been updated to
accommodate feedback from other researchers, it has not undergone rigorous peer-review
associated with submission to a research journal. Thus, the results contained in this report should
be interpreted as preliminary and suggestive. It is the goal of these authors to submit a
manuscript based on this report to a peer-reviewed journal in the near future.

The remainder of this report is organized as follows. We first provide an overview of fire safety
standards and identify those which are relevant to Pittsburgh and which can be operationalized
for this study. Next, we review the research literature related to quantitative planning models for
fire services. We follow with a presentation of three models for fire services design, one of
which is purely descriptive and the latter two of which are normative. Next we describe the data
used to implement these models, as well as modifications and validations performed to ensure
their appropriateness and accuracy. We then present computational results from the three
planning models and identify benchmarks for policy analysis. This is followed by a sensitivity
analysis, in which certain assumptions underlying the models are systematically modified to
identify common policy recommendations. The final section concludes and presents potential
modeling extensions.

**Historical Information**

In order to better understand the questions and problems facing Fire Protection Services, we
survey the history and evolution of the fire service industry in America. By reviewing the
managing models that fire chiefs and fire administrators reference, we were able to more fully
understand the dilemmas they encounter. These guidebooks stressed that there is not a universal
level of coverage to which a community must adhere. Instead, each community must ask itself:
(1) What level of risk the municipality is willing to accept?
(2) Who benefits and who is deprived under each option set?
(3) What is the scope, objective, and methods of the fire delivery system?
(4) What are a realistic set of options that can be implemented?5

Two major national guidelines exist that put forth recommendations for City service levels. These two guidelines are the Insurance Services Office, Inc. Fire Suppression Rating Schedule and the National Fire Protection Association’s NFPA 170, Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Specialty Operations to the Public by Career Fire Departments. Each of these guidelines put forth recommendations of the level of service a City should provide.

ISO is an independent organization that serves insurance companies, fire departments, insurance regulators, and others by providing information about risk. ISO collects information about municipal fire-protection efforts in communities throughout the United States. In each community, ISO analyzes the relevant data and assigns a Public Protection Classification—a number from 1 to 10. Class 1 represents exemplary fire protection, and Class 10 indicates that the area's fire-suppression program does not meet ISO's minimum criteria.6 ISO’s Fire Suppression Rating Schedule (FSRS) is the standard used to determine a City’s classification number. The distribution of fire stations is one of dozens of criteria used in the rating process. A City will receive credit for the portion of the City that has a first-due engine company within 1½ miles and a ladder-service company within 2½ miles.7

The National Fire Protection Association is a non-profit organization founded with a mission to reduce the worldwide burden of fire and other hazards on quality of life by providing and advocating scientifically-based consensus codes and standards, research, training and education.8 The National Fire Protection Association developed NFPA Standard 1710 through a voluntary consensus process as the standard to be used for all public fire departments. NFPA 1710 requires that firefighters respond within “four minutes (240 seconds) or less for the arrival of the first responding engine company at a fire suppression incident and/or eight minutes (480 seconds) or

---

6 This description was taken from the ISO website: http://www.iso.com/
7 Ibid. § 560-561.
8 This description was taken from the NFPA website: http://www.nfpa.org/
less for the deployment of a full first alarm assignment at a fire suppression incident” not less than 90 percent of the time.\(^9\)

The City of Pittsburgh relies predominantly on the NFPA guidelines. In their contracts they require the first responding engine company to arrive within four minutes and the entire first response battery (three engine companies, one truck company and the fire chief) to respond within eight minutes. We therefore focused on these measures in our analysis.

**Literature Review**

In order to formulate a model representative of the dilemma facing the City of Pittsburgh, we conducted a literature review of the existing body of work regarding the location of emergency service facilities. Beginning in the 1960’s operations researchers began studying the deployment of fire, police, and emergency medical units: each of these systems has as its objective to respond to calls for service as quickly as possible to reduce loss of life and injury. Operations research models have been created to either make existing resources more effective or to maintain effectiveness with fewer units. Modern models for fire service provision have their origin in “set-covering” type models, in which services are assumed to be provided to patrons within a certain distance of a facility (the patrons are “covered” by the facility) and not provided if the distance between patrons and the facility exceed this critical distance (the patrons are not “covered”). This “covering” notion is consistent with the fire service standards presented in the previous section. The goals of covering models are to determine the minimum number of facilities necessary to cover all demands, or alternatively the configuration of a fixed number of facilities that maximizes the number of demands served. Papers by Toregas, Swain, ReVelle and Bergman (1971) and Schilling, Elzinga, Cohon, Church and ReVelle (1979) are basic references in this area, and the text by Daskin (1995) remains a key compilation of facility location models and solution algorithms relevant to this problem.

After researching the City of Pittsburgh’s dilemma, we determined that the problem was to determine the “right” number of stations to cover demands for fire protection in the city of Pittsburgh. However, the notion of a “right” level of service is ambiguous and politically

---

sensitive. In this connection, A.J. Swersey states: “The challenge of implementation is particularly formidable in this field because emergency services operate in a highly politicized environment. For example, closing a fire station is difficult in the face of predictable opposition for militant unions, private citizens, and local politicians.”

Thus, to provide more resources to City decision makers, we created a portfolio of operations research models. One model is purely descriptive in nature; it uses the language of operations research-based covering models to represent the level of service associated with a given configuration of fire stations. The remaining two models are normative in nature; they provide specific recommendations regarding the configuration of fire stations necessary to optimize certain goals, or objectives. These models are intended to provide a host of options to decision makers as they choose alternative configurations of fire services to meet a variety of policy goals.

**Decision Support System**

We created a decision support system to aid City officials as they determine the appropriate level of fire protection for the City of Pittsburgh. This system is comprised of three unique models—each model answering a different question the City may consider when addressing the complex policy issue of fire protection:

- **Heuristic Model**—a simple tool to generate auditable data for any configuration of stations
- **Set-Covering Model**—an optimization model which answers “What is the minimum number of facilities and the location of these facilities necessary to meet a minimum service standard?”
- **Maximum Covering Location Model**—an optimization model which answers “Where should I place ‘X’ number of facilities to maximize the number of covered demands?”

This multiple-model approach was designed to reflect the policy imperatives of decision makers, address multiple policy goals they face, and generate a collection of policy alternatives. Outputs
of this system provide specific, structured and auditable guidance to decision makers participating in the public safety negotiation process. This decision support system is not intended to provide a single recommendation regarding public safety expenditures. Instead, it provides information regarding a collection of public safety strategies that offer, in some way, an improvement over current practice. This system is designed to help decision makers at the City level to identify specific service alternatives and gain deeper understanding of trade-offs between the cost, service and equity implications of these recommendations.

Below is outlined the purpose, intended users, and directions for use for each of the three models. This brief introduction is intended to provide a deeper understanding of the vast amount of information the decision support system is able to provide.\textsuperscript{11}

**Heuristic Model**

**I. Model Purpose**

The Heuristic Model is a simple tool to generate data for any configuration of facilities; it is not an optimization model. This model requires the user to select from among existing fire station facilities which will remain open. Based upon this proposed configuration of facilities, the model generates corresponding data: the percentage of the City covered according to both NFPA and ISO guidelines, percentage of the City with double, triple and quadruple coverage, average response time, percentage of the City’s population, area, and housing units covered, and other measures. This data can be generated for every possible configuration of facilities. It therefore allows for a side-by-side comparison of different facility configurations.

**II. Intended Users**

This model can be used to provide a simple, step-by-step analysis of service options to the City. It is intended to be used by decision makers as small changes are being negotiated and alternatives considered. For example, to determine whether or not to keep a given station open, this heuristic approach will be able to demonstrate the level of coverage the City will experience both with and without station. Therefore, the additional coverage and protection this station provides can be calculated. City decision makers will

\textsuperscript{11} The model statement, outlining the Purpose, Assumptions, Data, Decision Variables, and Model Objective Function for each model, is located in Appendix A. Additional technical information is available upon request by contacting the author.
then be able to decide whether the additional coverage provided by the station is sufficient to warrant the additional cost the station represents.

III. Model Use

The user begins by entering the desired facility configuration in the model. The model calculates various coverage measures that are associated with this configuration. Coverage measures include: the percentage of the City covered according to both NFPA and ISO guidelines; percentage of the City with double, triple and quadruple coverage; average response time; percentage of the City’s population, area, and housing units covered; and other measures. Once the output results have been calculated, a sensitivity analysis will be performed and the model will offer the possibility to improve upon the results obtained by either solving the Set-Covering Model or by solving the Maximum Covering Location Model with the same number of facilities as entered before.

Set-Covering Model

I. Model Purpose

The purpose of the Set-Covering Model is to answer the question “What are the minimum number of facilities and the location of these facilities necessary to meet a minimum service standard?” This model was based on the research of Constantine Toregas, Ralph Swain, Charles ReVelle, and Lawrence Bergman. To create this model, we began with a coverage matrix for each level of aggregation. This matrix states

---

whether the distance from a demand node (block, block group and census block) to a station location is within a specified distance parameter. A separate coverage matrix was created for each fire protection standard used. For example, according to the National Fire Protection Association guidelines (NFPA 1710), an engine station must be within a 4 minute drive for the first arriving company to be considered within the service parameter. All demand nodes within a 4 minute drive from a station are be labeled as within the service area of that particular station; all other demand nodes are labeled outside the service area. In addition, this calculation was done for 8 minutes travel times in order to calculate the triple coverage required for the first responding companies. Once these matrixes have been built, the model determines the minimum number of stations necessary so that a specified percentage of the City meets the guideline. Continuing the example from above, NFPA guidelines require that 90% of the city be within the service parameter to meet the guidelines. Once the model has run and the minimum configuration of stations has been determined, output data is generated and compiled by the model. This data includes the percentage of the City covered according to both NFPA and ISO guidelines; percentage of the City with double, triple and quadruple coverage; average response time; percentage of the population, area and housing units covered; and other measures. Once the output results have been calculated sensitivity analysis will be performed.

II. Intended Users

The Set-Covering Model determines the minimum number of facilities necessary that provide a certain level of coverage for a City. However, decisions made for a City are often not based upon the minimum necessary; other considerations must be factored in to the equation. Therefore this model provides an excellent starting point for the decision making process. It should be used by administrators and decision makers as they annually review the funding levels for the Bureau of Fire and anytime expansions or reductions are being considered. This model will help decision makers thoroughly consider whether the cost of facilities beyond the minimum necessary to meet federal and insurance guidelines is worth the additional protection and coverage they provide. In addition, this model should be updated whenever the standards of fire coverage are changed. Although the service standards required by either the National Fire Protection Association or ISO have
not changed in recent years, if they ever are adjusted, this model has the ability to quickly
determine the City of Pittsburgh’s service levels relative to these changes and whether the
current configuration of fire services needs to be changed in order to respond to the
change in requirements.

III. Model Use

The user begins by selecting the parameter representing the service level that facilities
generated by the model must meet. In this situation, the model will either meet the NFPA
1710 or ISO guidelines for engine and ladder facilities. These guidelines define the
percentage of the City that must be within a maximum distance (in either miles or travel
time) from a station. Once the model parameter has been selected, the model determines
the minimum number of stations necessary to meet the guideline. The model then
calculates the output results for this configuration including the percentage of the City
covered according to both NFPA and ISO guidelines; average response time; percentage
of the population, area and housing units covered; and other measures. Once the output
results have been calculated sensitivity analysis will be performed.

Maximum Covering Location Model

I. Model Purpose

The purpose of the Maximum Covering Location Model is to answer the question
“Where should I place ‘X’ number of facilities to maximize the number of covered
demands?” This model is based upon the work of David Schilling, D. Jack Elzinga, Jared
Cohon, Richard Church and Charles ReVelle in their creation of the Team/Fleet Models. To create this model, we first created a coverage matrix. This matrix states whether the distance from a census block to a station location is within a specified distance parameter for every census block and station. A separate coverage matrix was created for each fire protection standard used. For example, according to the National Fire Protection Association guidelines (NFPA 1710), an engine station must be within a 4 minute drive time for the first arriving company to be considered within the service parameter. All census blocks within a 4 minute drive miles from a station are labeled as within the service area of that particular station; all other census blocks are labeled as outside the service area. In addition, this calculation was done for 8 minutes travel times in order to calculate the triple coverage required for the first responding companies. Once this matrix has been built, the model determines which stations to select to provide the maximum amount of coverage to the City. Once the configuration of stations has been determined, output data is collected and compiled by the model. This data includes the percentage of the City covered according to both NFPA and ISO guidelines; percentage of the City with double, triple and quadruple coverage; average response time; percentage of the population, area and housing units covered; and other measures. Once the output results have been calculated sensitivity analysis will be performed.

II. Intended Users

The Maximum Covering Location Model determines the best configuration of a set number of facilities in order to maximize the coverage of the City. This can be very beneficial information as often the number of facilities that can be built is limited by budgetary or other considerations. This model selects the optimum location of facilities for a set number of facilities. However, determining how many facilities to locate is not an easy process. Since the exact number of facilities may be negotiable, this model can be run several times with differing constraints on the number of facilities to compare the added coverage provided from each additional facility. This model may also be run in tandem with the other models within the decision support system. This will help to generate several feasible alternatives to be considered.

III. Model Use

The user begins by selecting the number of facilities both (engine and ladder) the model will locate. Next, the user determines the coverage criteria to measure demand. In the Maximum Covering Location Model the measures of demand will be populations, housing units, land area, or census blocks. The model will then determine which station locations provide the best coverage according to the coverage measures. Once the best configuration of stations has been determined by the model, additional output data will be generated. This data includes the percentage of the City covered according to both NFPA and ISO guidelines; average response time; percentage of the population, area and housing units covered; and other measures. Once the output results have been calculated sensitivity analysis will be performed.

Data Compilation and Validation

Once the model formulations had been determined, we collected data representative of the City of Pittsburgh. In order to create a well-defined set of demand nodes, we represented the City on the basis of three commonly-accepted levels of spatial aggregation: Census blocks, block groups, and tracts. Pittsburgh, with a total land area of approximately 55 square miles is comprised of
7,501 census blocks, 343 census block groups and 200 census tracks. On average, each census block represents 0.0234 square miles, 66 housing units, and a population of 139 people; each census block group represents 0.080 square miles, 204 housing units, and a population of 411 people; each census tract represents 0.397 square miles, 817 housing units and a population of 1,573 people\textsuperscript{14}.

Next, the centroid of each census block, block group and tract was calculated. For the purpose of this project, all calls for fire service are assumed to occur at these locations. Thus, using the language of “covering”, a spatial region such as a block group is “covered” (served) by a fire station if its centroid is within a given distance standard of the station, this standard being derived from fire safety standards presented in the previous section. Moreover, we assume that the probability of a call for service is proportional to standard Census measures presented above, i.e. population or number of housing units.

Next, we entered the existing fire stations into the model. Each fire station is located using its geographic coordinates, which usually do not correspond to centroids of Census-defined units. The City of Pittsburgh presently has 33 engine stations and 11 truck stations, some of which are co-located. The models used in this report only consider closing existing facilities; no new facility locations were considered.

Finally, information regarding the layout of the City of Pittsburgh was compiled. Pittsburgh is located at the union of three rivers—the Allegheny, Monongahela, and Ohio. It is also has severe changes in altitude. Due to the unique topography of the City, it would be grossly inaccurate to calculate the service areas of the fire stations as concentric circles emanating from each station. Instead, a road map of the City was generated which served as the source for all distance and travel time calculations. This road map was used to calculate a distance matrix—stating the distance from every fire station to every demand node or census block—and coverage matrices—stating whether or not the distance from a fire station to a demand node is within a set parameter. A different coverage matrix was created for each guideline considered, each level of aggregation and for both engine and truck stations.

Calculating the ISO coverage matrix was relatively straight-forward. ISO guidelines require a station to be within a set distance parameter (1½ miles for each engine station and 2½ miles for

\textsuperscript{14} Extensive details regarding Census spatial units are available from the Bureau of the Census, www.census.gov.
each truck station). The road map was used to calculate the distances and therefore the coverage area for each station.

NFPA 1710, however, requires stations to be within set drive time in order to be considered covered (4 minute drive time for first-responding engine stations and 8 minute drive time for full first-responding assignment). In order to calculate coverage areas under NFPA 1710 a driving speed for fire trucks must be estimated. Using posted speed limits was clearly an overstatement of the speed at which fire engines and trucks could travel, but there are no national or local guidelines suggesting the appropriate rate of travel. The Mayor’s staff provided a street map with and estimated rate of travel for street segment in the City. These speed limits ranged from 15 to 55 mph. The most common rate of travel was 25 mph; 45 and 55 mph assumptions were only estimated on highways.\textsuperscript{15} This map and corresponding speed limits served as the basis for my NFPA coverage model.

In order to test the accuracy of the city map, we gathered data from the Bureau of Fire regarding all fire incidents in the City during years 2000 (1,456 incidents), 2001 (1,467 incidents), and 2002 (1,116 incidents). This data lists the location of the incident, the first responding station, and the drive time observed from that station. Next, using the City street map, we calculated the drive times using my speed limit assumptions. Finally, we compared these values to see how closely my estimates compared with those observed by existing fire stations. Our model generated an average response time of 124 seconds and a standard deviation of 94 seconds. The fastest estimated response time was 1 second and the slowest was 768 (13 minutes). The data actually recorded by the Bureau of Fire had an average response time of 142 seconds with a standard deviation of 76 seconds. The fastest estimated response time was 0 seconds (observed 123 times) and a slowest response time of 734 seconds (12 minutes).\textsuperscript{16} When you compare the recorded drive times with the estimated drive times from the model, you observe that the model estimates, on average, a drive time 18 seconds faster than those recorded by the Bureau of Fire. Although we are not able to say with certainty the “correct” drive time estimate, we can however, point out several possible reasons for the observed discrepancy.

\textsuperscript{15} The street map of Pittsburgh contains 36,122 line segments. The most common rate of travel estimated was 25 mph (29,861 street segments or 83% of all roads). 15 mph was estimated as the rate of travel for 16% of all Pittsburgh roads; all other speeds (>30 mph) were estimated to occur on less than 1.7% of Pittsburgh’s roads.

\textsuperscript{16} The following calculations were performed on an edited version of the Bureau of Fire data. We first eliminated all negative drive times (32 observations) and then calculated the summary statistics.
The first possible reason for the difference between the estimated and observed drive times is flawed data from the Bureau of Fire. Several glaring errors were found within the data including severely negative estimates of drive times and multiple estimates of a drive time of zero. With the existence of such large errors in the dataset, it calls into question the overall reliability of the observations.

A second possible reason for the observed difference in drive times stems from the nature of the models created. The decision support system created is by design a deterministic model. It does not account for situations in which stations are responding to other calls, a traffic jam exists, or severe weather conditions delays the arrival of trucks. In other words, these models provide an estimate of coverage assuming ideal conditions. Although this is indeed a simplification of the circumstances that exist for firemen, it is still a very useful tool. Adverse conditions can be built into the model by providing back-up and duplicative coverage.

A third possible explanation for the observed difference in drive time estimates is that the speed limits calculated by the City street map under-estimate the time it takes for a truck to drive the streets of Pittsburgh.

Although we did not determine the level to which each of these scenarios impact the observed difference in travel time, we have incorporated these possible errors into my model by analyzing the coverage realized from the base estimate and an adapted model of the travel time estimate. These calculations and their implications are examined further in the Sensitivity Analysis section of the paper.

**Model Results**

After the data had been collected and examined, we implemented the heuristic model to analyze the City of Pittsburgh’s existing configuration of stations. Figure 1 presents a picture of the City with all 35 existing stations (33 engine stations and 11 truck stations). Figures 2 and 3 present the coverage area of the City of Pittsburgh according to NFPA 1710 coverage criteria for engine and truck stations respectively using demands for fire services represented as Census block centroids.

---

17 Nine stations house both engine and truck facilities. Therefore the total number of stations is not equal to the sum of the engine and truck stations.
As these images demonstrate, the preponderance of the City is covered according to NFPA guidelines for both engine and truck facilities. In fact, 98% of the City is covered by engine stations and 99% of the City is covered by truck stations and the furthest distance from a station to a census block is 3.5 miles. In addition, this configuration of stations provides an abundance of double and triple coverage. 87% of the City has double coverage from the engine stations and 60% has triple; 88% of the City has double coverage from the truck stations and 76% has triple coverage.

---

18 The model is able to generate substantial additional data for every configuration of stations including information on percentage of the City land area covered, percentage of the City population covered, and percentage of the housing stock covered, average distance from a station, and maximum distance to a station.
After analyzing the existing configuration of stations and realizing the level of duplicative coverage, we next implemented the set-covering model to determine the minimum number of stations necessary to meet the NFPA 1710 standards for both engine and truck stations, with demands treated as Census block centroids. After formulating this model using AMPL Version 8.0 (ILOG CPLEX Division 2003a) and solving the model using CPLEX Version 8.0 for AMPL (ILOG CPLEX Division 2003b), we found that 12 engine companies covered the 91% of the city.
once, 13% twice and 0% three times, and that 4 truck companies covered 91% of the city once, 43% twice and 13% three times. Figures 4 and 5 show coverage results for this model.

Since duplicate coverage is an important consideration in fire services protection, we do not advocate this particular configuration as a basis for policy discussions. Instead, these results
represent, in a sense, a lower bound on the number of fire companies that would be necessary to satisfy NFPA 1710 guidelines, strictly interpreted.

Another more realistic example of a configuration of fire stations that preserves a high level of public safety is based on the maximum covering model. In this case, we used population counts assigned to each Census block centroid to determine the spatial configuration of 20 engine companies and 8 truck companies that would maximize the amount of demand covered using NFPA 1710 guidelines. Figure 6, below, shows that 98% of city is covered once by engine companies, 51% is covered twice and 8% is covered three times.

![Figure 6: City Coverage, NPFA 1710 Standard, Max Covering Model, 20 Engine Companies](image)

Figure 6, below, shows that 98% of city covered once by truck companies, 77% is covered twice, and 57% is covered three times.
Extending the analysis presented above, we ran the maximum covering model for all three levels of aggregation for the City (Census blocks, block groups and tracts) and required that the first responding engine arrive on the scene within four minutes 90% of the time and that the entire first responding assignment (three engine companies and one ladder company) arrive within eight minutes 90% of the time. Model results indicate that eliminating nine engine companies (27% of the total) and five truck stations (45% of the total) still maintained a level of service such that all coverage measures (demand nodes, population, housing units, and land area) record, at a minimum, 90% coverage for all three levels of aggregation. In addition, these reductions still provide for triple coverage for engine stations at a minimum of 90% and double coverage for truck stations (which is not required according to NFPA guidelines) at a minimum of 55%.

Due to the fact that each level of aggregation arrived at slightly different solutions, we do not propose one exact “optimum” configuration. There are many solutions that may be desirable to various stakeholders based on their interpretations of acceptable levels of service quality. Instead, we assert that decisionmakers may use results such as these to choose a most-desired configuration of fire stations based on common modeling and data assumptions and policy preferences outside the scope of these models.
Sensitivity Analysis

In this section of the report, we present sensitivity analysis of model parameters. Sensitivity analysis is intended to provide model users with information regarding the impact adjusting one parameter of the model will have upon the outcome generated. In this section, we analyze how changing the number of stations affects the overall coverage of the City, information regarding the trade-offs between cost and coverage the decision support system generates, and how adjusting the estimated rates of travel impact the coverage areas generated, information regarding the significance of speed limit selection.

We begin with an analysis of the trade-offs between number of stations located and City coverage. This information presents the reality that City decision makers are facing as they debate the appropriate coverage level for the City. It is a simple fact that the more stations provide more coverage or more redundant coverage. However, the City has stated they must close stations due to financial considerations. This section will provide information regarding the cost these station closings will have for the citizens of Pittsburgh.

Figure 8 demonstrates the trade-offs associated with the addition of one engine station on the City in terms of coverage loss for each level of aggregation. This graph clearly demonstrates the falling marginal benefit from the addition of another engine station. The first engine stations provided provide the most additional coverage to the City while the last few stations provide none.

Figure 8: Population Coverage, Different Levels of Demand Aggregation, Engine Companies
Figure 9 demonstrates the same trade-offs examined above but now analyzing truck stations. Once again this graph demonstrates the falling marginal benefit associated with the addition of truck stations for all levels of aggregation. The addition of the first few truck stations provide the most marginal benefit to the City while the last few stations provide no additional coverage.19

![Coverage Area vs. Number of Stations](image)

Figure 8: Population Coverage, Different Levels of Demand Aggregation, Engine Companies

We now turn to an analysis of the rate of travel estimation and its implication on the output generated by the model. As stated in the Data Analysis and Validation section of the paper, rates of travel had to be estimated in order for coverage areas to be calculated according to NFPA 1710 guidelines. City officials had generated a street map of the city and estimated rates of travel on every road segment in the City. We used this street map to determine whether an individual census block was within the coverage area of an engine or truck station. When comparing travel times recorded by the Bureau of Fire to the times estimated by my model, we determined that model estimates were, on average, 18 seconds faster than those from the BoF. In order to determine the impact on the model results of such an under-estimate, we created a coverage matrix based on a travel time of 220 seconds for engine stations (3:40 seconds: subtracting 20 seconds from the national guideline of 4 minutes) and 460 seconds for truck stations (7:40 seconds: subtracting 20 seconds from the national guideline of 8 minutes).

19 This trade-off analysis is regarding additional truck stations and single-coverage according to NFPA 1710 guidelines.
With this new coverage matrix, we used the heuristic model to analyze the City’s existing configuration of stations—the same analysis performed above, using block-level demands. With this reduced coverage area, the City experiences 97% of the City covered according to NFPA 1710 engine guidelines and 99% of the City covered according to NFPA 1710 truck guidelines. 78% of the City experiences double coverage from the engine stations and 50% of the City experiences triple coverage. 86% of the City experiences double coverage from the truck stations and 73% of the City experiences triple coverage. Comparing these figures with the previous results obtained, we realize less than a 1% decrease in coverage with the adjusted coverage areas. The double coverage from engine stations falls by approximately 10% and triple coverage falls by 17%. The double can triple coverage realized by the truck stations remains nearly identical. Figures 9 and 10 demonstrate the coverage of the City with these adjusted coverage areas. Thus, the reduction in coverage areas has minimal affect on the estimated existing coverage of the City.

Figure 9: City Coverage, Reduced Coverage Area Estimates, Current Configuration, 33 Engine Companies
The reduced coverage area does however, have a material effect on the number of stations needed when performing the set-covering model. Previously when minimizing the number of stations necessary to meet the NFPA 1710 guidelines only 12 engine stations and 4 truck stations were needed. With the adjusted coverage area, 15 engine stations and 4 truck stations are necessary. Figures 11 and 12 represent the revised configuration of engine and truck stations respectively. This represents an increase in engine stations of 25% while the number of truck stations remained the same. The change in coverage is not so dramatic when you compare the coverage observed with the original coverage matrix and the coverage observed with the revised coverage matrix. Engine station coverage area falls from 95% to 90% of the City covered—a reduction of 5%; truck station coverage area falls from 91% to 90% of the City covered—a reduction of 1%. Thus the impact of reducing the coverage areas by 20 seconds travel time has only a nominal effect on the coverage area of the City.
Conclusion

This report represents a preliminary effort to provide insight into an important policy concern, public safety expenditures, specifically, location of fire stations in an urban setting. The troubled status of the city of Pittsburgh’s financial health have motivated our efforts to understand the likely impacts of alternative strategies to reduce public expenditures for fire services. The models described in this paper provide a consistent, evidence-based and data-driven framework for the
difficult process of choosing recommendations for the level of fire service reductions that the
City may perform while still maintain the necessary levels of coverage for City residents.

We have shown that while the current level of fire services provision results in a substantial
portion of the city that is covered multiple times according to NFPA guidelines for engine and
truck companies. In addition, we have shown that models that choose locations of fire companies
to maximize demands served for various fire safety subject to limitations on the number of fire
companies and accounting for NFPA service standards generate levels of fire service that
represent potential substantial savings with negligible impacts on service quality measures.
While the planning models presented in this paper use a variety of simplifying assumptions, it is
our belief that the results shown in this paper indicate significant opportunities for savings in fire
service expenditures that do not degrade service quality.

There are a number of extensions to the work in this report that may result in more accurate
planning models. First, our measure of demand for fire services was based on Census counts of
population and households. Though these measures are certainly preferable to no measures at all,
most desirable would be demands for fire service derived from historical counts of fire service
calls, aggregated to various spatial levels. The Bureau of Fire has provided us with these data,
however we used them only to validate travel times. An obvious next step then is to use
historical data on requests for fire service as the primary measure of demand in our models. A
second modeling extension addresses the fact that demands for fire service are not perfectly
random over time; calls may “bunch up” based on time of day or day of week. This in turn
presents the possibility of certain fire stations being unavailable to answer incoming requests for
service if their equipment are already used to respond to other calls. As a result, it may be that
fire stations other than the ones closest to the request for service may be required to respond to
the call, increasing response times beyond those estimated for modeling purposes. This factor
can be accommodated in our models by addressing explicitly the randomness in demands for fire
service and estimating the probability that a given fire station may be unable to respond to a
request for service. Daskin (1995) and others have incorporated these considerations into facility
location models successfully using elements of an operations research-related discipline called
queueing theory. Finally, it is reasonable to assume that planning models for fire service might
optimize multiple criteria simultaneously, for example, maximizing demands while minimizing
costs, or minimizing costs while maximizing perceptions of fairness in fire station location
among stakeholders. This is an example of multiobjective analysis, and multiobjective math programming has been a standard analytical method in operations research for over thirty years. A standard reference in this area is Cohon (1977).

Despite the limitations of our work, we believe that it can add real value to difficult and contentious discussions regarding most-appropriate configurations of public safety services, especially fire safety services. We look forward to the future discussions of City decision makers and hope that this insight provided by this decision support system aids the process of rationalizing the level of city services. We plan to revisit this research to address the modeling extensions presented above and to submit a manuscript based on this report to a peer-reviewed academic journal in the near future.
Appendix A: Model Statements

I. Heuristic Model

Purpose

The purpose of the heuristic model is to calculate multiple measures of coverage for the City for a selected configuration of facilities.

Assumptions

- All user demands can be represented as occurring at a finite set of points (Census block centroids);
- All service facilities, both engine and ladder, are also a finite set of points (existing fire stations), no new station locations were considered;
- Engine and ladder facilities may be located independently, or may be located jointly in one facility.
- The distance or response time between any demand node and service facility pair is known.

Sets

\[ I \] = the set of demand nodes
\[ J \] = the set of potential facility locations

Data

\[ D^e \] = distance standard for engine facilities (ISO or NFPA)
\[ D^l \] = distance standard for ladder facilities (ISO or NFPA)
\[ d^e_{ij} \] = distance from demand node \( i \) to engine station \( j \)
\[ d^l_{ij} \] = distance from demand node \( i \) to ladder station \( j \)
\[ x^e_j \] = 1 if an engine facility is located at node \( j \)
\[ 0 \] otherwise,
$$x^l_j = \begin{cases} 1 & \text{if a ladder facility is located at node } j \\ 0 & \text{otherwise,} \end{cases}$$

$$a^e_{ij} = \begin{cases} 1 & \text{if } d^e_{ij} \leq D^e \\ 0 & \text{otherwise,} \end{cases}$$

$$a^l_{ij} = \begin{cases} 1 & \text{if } d^l_{ij} \leq D^l \\ 0 & \text{otherwise,} \end{cases}$$

**Model Decision Variables**

This model contains no decision variables. The user will select whether or not a station remains in service.

**Model Objective Function**

This model does not have an objective function. The user enters the configuration of stations and output is generated based upon the configuration.
II. Set-Covering Model

Purpose

The Set-Covering Model minimizes the total number of facilities (both engine and ladder) necessary to meet a minimum coverage standard.

Assumptions

- All user demands can be represented as occurring at a finite set of points (Census block centroids);
- All service facilities, both engine and ladder, are also a finite set of points (existing fire stations), no new station locations were considered;
- Engine and ladder facilities may be located independently, or may be located jointly in one facility;
- The distance or response time between any demand node and service facility pair is known.

Sets

$I = \text{the set of demand nodes}$

$J = \text{the set of potential facility locations}$

Data

$D^e = \text{distance standard for engine facilities}$

$D^l = \text{distance standard for ladder facilities}$

$d_{ij}^e = \text{distance from demand node } i \text{ to engine station } j$

$d_{ij}^l = \text{distance from demand node } i \text{ to ladder station } j$

$\alpha^e = \text{coverage standard for engine facilities}$

$\alpha^l = \text{coverage standard for ladder facilities}$

$a_{ij}^e = 1 \text{ if } d_{ij}^e \leq D^e$
\[ a_{ij}^l = \begin{cases} 1 & \text{if } d_{ij}^l \leq D^l \\ 0 & \text{otherwise}, \end{cases} \]

\[ N = \text{total number of demand nodes} \]
\[ M = \text{total number of facility locations} \]

**Decision Variables**

\[ x_j^e = \begin{cases} 1 & \text{if an engine facility is located at node } j, \\ 0 & \text{otherwise}, \end{cases} \]
\[ x_j^l = \begin{cases} 1 & \text{if a ladder facility is located at node } j, \\ 0 & \text{otherwise}, \end{cases} \]
\[ z_j = \begin{cases} 1 & \text{if a facility is located at node } j, \\ 0 & \text{otherwise}, \end{cases} \]
\[ y_i^e = \begin{cases} 1 & \text{if demand node } i \text{ is covered by an engine station,} \\ 0 & \text{otherwise}, \end{cases} \]
\[ y_i^l = \begin{cases} 1 & \text{if demand node } i \text{ is covered by a ladder station,} \\ 0 & \text{otherwise}, \end{cases} \]

**Model Objective Function**

**Minimize**

\[ z_j = \sum_{j=1}^{j=M} x_j^e + x_j^l \]

**subject to**

\[ \sum_{j \in J} a_{ij}^e x_j^e \geq y_i^e \quad \text{for all } i \in I \] (1)
\[ \sum_{j \in J} a_{ij}^l x_j^l \geq y_i^l \quad \text{for all } i \in I \] (2)
\[ \sum_{j \in J} y_j^e \geq \alpha^e N \] (3)
\[ \sum_{j \in J} y_j^l \geq \alpha^l N \quad (4) \]

\[ x_j^e = 0,1 \quad \text{for all } j \in J \quad (5) \]

\[ x_j^l = 0,1 \quad \text{for all } j \in J \quad (6) \]

\[ z_j = 0,1 \quad \text{for all } j \in J \quad (7) \]

\[ y_i^e = 0,1 \quad \text{for all } i \in I \quad (8) \]

\[ y_i^l = 0,1 \quad \text{for all } i \in I \quad (9) \]

The Model Objective Function is to minimize the sum of all facilities (engine plus ladder facilities) subject to the following constraints: (1) The number of facilities that cover/serve node \( i \) according to the engine distance requirements must be greater than or equal to decision variable \( y_i^e \) (a node is covered by an engine station if it can be served by engine stations located on the network); (2) The number of facilities that cover/serve node \( i \) according to the ladder distance requirements must be greater than or equal to decision variable \( y_i^l \) (a node is covered by a truck station if it can be served by truck stations located on the network); (3) The fraction of all demand nodes served by engine stations must meet or exceed coverage standard \( \alpha^e \); (4) The fraction of all demand nodes served by ladder stations must meet or exceed coverage standard \( \alpha^l \); Constraints (5) and (6) are binary constraints stating that decision variable \( x \) will be equal to either 0 or 1 depending on whether an engine or ladder facility is located at point \( j \); Constraint (7) is a binary constraint stating that decision variable \( z \) will be equal to either 0 or 1 depending on whether a facility is located at location \( j \); Constraints (8) and (9) are binary constraints stating that decision variable \( y \) will be equal to either 0 or 1 depending on whether the demand node is covered by an existing engine or ladder facility.
III. Maximum Covering Location Model

Purpose

The Maximum Covering Location Model maximizes the number of covered demands by both engine and ladder stations.

Assumptions

- All user demands can be represented as occurring at a finite set of points (Census block centroids);
- All service facilities, both engine and ladder, are also a finite set of points (existing fire stations), no new station locations were considered;
- Engine and ladder facilities may be located independently, or may be located jointly in one facility.
- The distance or response time between any demand node and service facility pair is known.

Sets

\[ I = \] the set of demand nodes

\[ J = \] the set of potential facility locations

Data

\[ P^e = \] the number of engine facilities to be located,

\[ P^l = \] the number of ladder facilities to be located,

\[ P^z = \] the total number of facilities to be located,

\[ D^e = \] distance standard for engine facilities,

\[ D^l = \] distance standard for ladder facilities,

\[ d^e_{ij} = \] distance from demand node \( i \) to engine station \( j \)
\[ d_{ij}^l \quad \text{distance from demand node } i \text{ to ladder station } j \]

\[ a_{ij}^e = \begin{cases} 1 & \text{if } d_{ij}^e \leq D^e \\ 0 & \text{otherwise,} \end{cases} \]

\[ a_{ij}^l = \begin{cases} 1 & \text{if } d_{ij}^l \leq D^l \\ 0 & \text{otherwise,} \end{cases} \]

\[ h_i = \text{demand at node } i \text{ (population, housing units, area, etc.)} \]

**Decision Variables**

\[ x_{ij}^e = \begin{cases} 1 & \text{if an engine station is located at node } j \\ 0 & \text{otherwise,} \end{cases} \]

\[ x_{ij}^l = \begin{cases} 1 & \text{if a ladder station is located at node } j \\ 0 & \text{otherwise,} \end{cases} \]

\[ z_j = \begin{cases} 1 & \text{if a facility is located at node } j \\ 0 & \text{otherwise,} \end{cases} \]

\[ y_{ij}^e = \begin{cases} 1 & \text{if node is covered by an engine stations} \\ 0 & \text{otherwise,} \end{cases} \]

\[ y_{ij}^l = \begin{cases} 1 & \text{if node is covered by a ladder stations} \\ 0 & \text{otherwise,} \end{cases} \]

**Model Objective Function**

Maximize \[ Z = \sum_{i \in I} h_i y_{ij}^e + h_i y_{ij}^l \]

subject to

\[ \sum_{j \in J} y_{ij}^e \leq a_{ij}^e x_{ij}^e \quad \text{for all } i \in I \quad (10) \]
The Model Objective Function is to maximize the number of covered demands subject to the following constraints: (10) The demand at node $i$ cannot be covered unless at least one engine station that covers node $i$ is selected; (11) The demand at node $i$ cannot be covered unless at least one ladder station that covers node $i$ is selected; (12) The number of engine facilities that are located cannot exceed $P^e$ facilities; (13) The number of ladder facilities that are located cannot exceed $P^l$ facilities; (14) The total number of facilities that are located cannot exceed $P^z$ facilities; (15) An engine facility can only be located at a site where a facility has been located; (16) A ladder facility can only be located at a site where a facility has been located; Constraint (17) is a binary constraint stating that decision variable $x_j$ will be equal to either 0 or 1 depending on whether an engine facility is located at point $j$; Constraint (18) is a binary constraint stating that decision variable $x_j$ will be equal to either 0 or 1 depending on whether a ladder facility is located at point $j$; Constraint (19) is a binary constraint stating that decision variable $z_i$ will be
equal to either 0 or 1 depending on whether a facility is located at location \( j \); Constraint (20) is a binary constraint stating that decision variable \( y_i \) will be equal to either 0 or 1 depending on whether demand node \( i \) is covered by an engine facility; Constraint (21) is a binary constraint stating that decision variable \( y_i \) will be equal to either 0 or 1 depending on whether demand node \( i \) is covered by a truck facility.
Appendix B: Bibliography


ILOG-CPLEX Division. 2003a. AMPL Version 8.0. Incline Village, NV.

ILOG-CPLEX Division. 2003b. CPLEX 8.0 for AMPL. Incline Village, NV.


