SANDIA REPORT

SAND2014-3416
Unlimited Release
Printed April 2014

Safety, Codes and Standards for Hydrogen Installations: Hydrogen Fueling System Footprint Metric Development

A.P. Harris, Daniel E. Dedrick, Chris LaFleur, Chris San Marchi

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia National Laboratories

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865) 576-8401
Facsimile: (865) 576-5728
E-Mail: reports@adonis.osti.gov
Online ordering: http://www.osti.gov/bridge

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd.
Springfield, VA 22161

Telephone: (800) 553-6847
Facsimile: (703) 605-6900
E-Mail: orders@ntis.fedworld.gov
Online order: http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online

SAND2014-3416
Unlimited Release
Printed April 2014

Safety, Codes and Standards for Hydrogen Installations: Metrics Development and Benchmarking

A.P. Harris, D. E. Dedrick, C. LaFleur, C. San Marchi
Sandia National Laboratories
P.O. Box 969, MS 9042
Livermore, CA 94551

Abstract

Automakers and fuel providers have made public commitments to commercialize light duty fuel cell electric vehicles and fueling infrastructure in select US regions beginning in 2014. The development, implementation, and advancement of meaningful codes and standards is critical to enable the effective deployment of clean and efficient fuel cell and hydrogen solutions in the energy technology marketplace. Metrics pertaining to the development and implementation of safety knowledge, codes, and standards are important to communicate progress and inform future R&D investments. This document describes the development and benchmarking of metrics specific to the development of hydrogen specific codes relevant for hydrogen refueling stations. These metrics will be most useful as the hydrogen fuel market transitions from pre-commercial to early-commercial phases.

The target regions in California will serve as benchmarking case studies to quantify the success of past investments in research and development supporting safety codes and standards R&D.

ACKNOWLEDGMENTS

This report acknowledges the investments from the Department of Energy Office of Energy Efficiency, and Renewable Energy (EERE), Fuel Cell Technologies Office (FCTO).

CONTENTS

FIGURES

TABLES

1. INTRODUCTION

1.1. Background

A number of automotive manufacturers are in the process of commercializing fuel cell electric vehicles (FCEV) in markets that have retail hydrogen fuel available. Hyundai, Toyota, and Honda began producing commercial vehicles in 2014 while other manufactures such as GM, Daimler, and Nissan, have all indicated plans for the 2015 to 2020 timeframe. Anticipated first markets for FCEVs include the US (the State of California), the EU (Germany), and Asia (Japan). The vehicles commercialized in 2014 and 2015 utilize a high-pressure (700 bar) composite storage tank, which requires fueling hardware at pressures up to 862 bar. The availability of hydrogen fuel and the cost of the fueling systems remain challenges to the full-scale commercialization of FCEVs. Much of the availability and cost issues are connected to the footprint required for fueling systems as directed by current fire codes.

The development of meaningful and science-based fire codes helps accelerate the deployment of hydrogen systems by helping to avoid overly-conservative approaches to commercial hydrogen fuel installations. Hydrogen codes and standards have been developed and are in the process of being implemented. Current efforts are focused on optimizing and refining the codes by implementing better safety information to reduce uncertainty and eliminate overly-conservative approaches. The Fuel Cell Technologies Office (FCTO) of the U.S. Department of Energy (DOE) describes meaningful codes and standards development as activity to "enable widespread deployment and commercialization of hydrogen and fuel cell technologies, by supporting research and development that provide experimentally validated fundamental understanding of the relevant physics, critical data and safety information needed to define requirements for technically sound and defensible codes and standards." [1]

1.2. The role of metrics

Very few quantifiable metrics have been defined relative to the development of meaningful codes and standards. Since most hydrogen-specific codes and standards already exist, the number of codes or standards is not an effective metric to indicate progress in the implementation for Safety Codes and Standards information and accelerating the deployment of clean and efficient hydrogen and fuel cell systems. A new metric or set of metrics need to be developed to quantify impact, show evidence of supporting market growth, and guide future R&D investments.

2. METRIC DEFINITION

A new metric to quantify impact and indicate success in the development of codes and standards has been defined as the "*number of fueling stations that can readily accept hydrogen*". This metric addresses the primary barrier to the commercial success of FCEVs: fuel availability.

A site can readily accept hydrogen when the following key criteria are met:

- No statutory or regulatory barriers exist.
- No local ordinance violations exist.

- A viable business case exists for integration of hydrogen fuel (for example, a site that already accommodates vehicle fueling located in a target FCEV market area).

One of the most influential factors impacting this metric is the lot line perimeter size and associated safety separation distances as required by the existing codes and standards. For example, in the *Hydrogen Technologies Code* (NFPA 2) from the National Fire Protection Agency (NFPA), a separation distance of 100 feet (30.5 m) from all classes of flammable and combustible liquids is recommended for bulk liquid hydrogen storage greater than 15,000 gallons (56,780 liters) [2].

It was recognized early on that separation distances presented a large challenge to siting hydrogen in a retail fueling setting (i.e. urban service station). Much of the work to date has been an ad-hoc private/public collaboration to change the hydrogen-specific code development process from an expert opinion-based system to a system where scientific data provides the basis for the code requirements; this science basis includes quantitative evaluation of hydrogen releases and integration of this data into a risk-informed approach [3][4][5][6]. This method has resulted in scientifically-defensible safety requirements including the separation distances. Therefore this benchmarking effort focuses on the impact of the change from expert opinion based to risk informed based separation distances.

There are many other important factors that are also critical for the acceleration of hydrogen systems into the commercial fuel market such as training and community outreach. The importance of these factors are not minimized, however, this metric focuses on the technical factors that can be influenced by enhanced scientific understanding and better approaches for quantifying risk.

There are additional options for developing sub-metrics related to this broad metric. Such sub-metrics might be: "The number of hydrogen sites that can readily accept hydrogen within 1 mile of freeway exits" or "The number of hydrogen sites that can readily accept cost competitive renewable hydrogen" or "The number of hydrogen sites that can readily accept hydrogen in demographically favorable areas with an average driving time of ## minutes".

3. BENCHMARKING

To effectively benchmark the new metric of the "number of sites that readily accept hydrogen", the Sandia team focused on geographic areas where hydrogen-fueling sites are being actively developed. In the US, the State of California is the focus of the development of retail hydrogen fueling stations. There are 9,710 retail gasoline stations in California. In a recent draft Public Opportunity Notice (PON) [7], a state funding announcement, the California Energy Commission (CEC) identified primary and secondary priority locations for fueling stations. Of the 9,710 total sites in California, there are 343 designated retail gasoline stations in these primary and secondary priority locations. A sample of the locations was taken and each of these sites was evaluated for readiness to integrate hydrogen; this assessment is based solely on compliance to the prescriptive requirements of the applicable hydrogen code, namely NFPA 2. Comparisons of two versions of the code are considered: the current code based on a risk-informed approach (2011 edition of NFPA 2) and previous editions of code based on expert opinion and experience (e.g., 2005 edition of NFPA 55). A description of the benchmarking process is described with results and analysis in the following sections.

3.1. Current separation distance requirements

The actual requirements for siting hydrogen at a retail station are generally challenging to determine. Several sources can be readily located but none are comprehensive. Therefore, two reference stations were created to ensure a common reference. These stations were then analyzed to determine whether a hydrogen station could be sited in actual locations using the most recent code for separation distances. Table 1 summarizes the separation distances for gaseous hydrogen storage (GH2) and liquid hydrogen storage (LH2) from the 2011 edition of NFPA 2. These separation distances summarize the distances most critical to the area required for siting a hydrogen fueling system and are used in the siting analysis. NFPA 2 separates gaseous and liquid supply systems into separate categories with different separation distances for each. The separation distances for gaseous systems are based on the size of the line connected to the supply system and the pressure, whereas the liquid separation distances are based on the volume of liquid. Both gaseous and liquid systems are given allowances to reduce separation distances based on the use of mitigation equipment. For gaseous hydrogen, a barrier wall can be used for mitigation (2-hour fire rated structure that disrupts the line of sight of the system). For liquid systems, the separation distance is reduced when insulation is used.

To demonstrate the relative size of the hydrogen system in an existing gasoline station, Figure 1 (GH2) and Figure 2 (LH2) show the hydrogen systems described in Table 1 for a retail fueling site with a footprint of 18 ,000 ft^2 (1,672 m^2). The critical separation distances (lot lines – yellow, air intakes and building opening – blue, classified electrical – red) are shown to scale in these figures. The GH2 station (Figure 1) has a 100 kg/day capacity with a 3 bank cascade fueling system with a tube trailer supply, compressor and other controls equipment located inside the 2-hour fire-rated walled equipment area. The small circles outside of the walls are vehicle protection or bollards. The GH2 reference station requires about 5,500 ft^2 (511 m^2) of space with at least one side no shorter than 21 meters in length. There is allowance to overlap the separation distances for buildings and ventilation intakes with the physical building, as the HVAC intake and building access doors may not be on the side of the building closest to the hydrogen equipment.

It is important to point out that actual siting of hydrogen stations can be a flexible process with local officials; in general, negotiation of system permitting occurs through an iterative process and the zoning of adjacent properties.

Figure 2 shows the liquid hydrogen fueling reference station with separation distances similar to the gaseous system depicted in the same colors. The retail station store and fueling pumps have been moved relative to the gaseous system to accommodate the liquid storage separation distances while the lot size remains 18,000 ft^2 (1,672 m^2). It must be noted that the liquid system shown includes a vertical tank and a cryogenic compressor, which minimizes the equipment footprint. It is very unlikely that early hydrogen stations will include a vertical hydrogen tank as the aesthetics for most jurisdictions would not allow such equipment in a retail setting. Therefore a horizontal tank would be more realistic and require separations distances that exceed the site boundaries for the 18,000 ft^2 (1,672 m^2) lot.

Table 1 –Summary of separation distances from NFPA 2 (2011 edition) – critical distances used in developing the diagrams in this report are shown in bold.

Separation Distances and Areas Required		
Fuel system descriptions: GH2 – 12,500 psi (862 bar) storage, 100 kg, 0.4 in (10 mm) ID tubing with a barrier wall LH2 – 3,500 - 15,000 gallon (13,250-56,780 liters) with barrier wall and insulation	GH2 ft (m)	LH2 ft (m)
Lot lines	**24 (7.3)**	**33 (10)**
Public streets, alleys	24 (7.3)	33 (10)
Parking (public assembly)	13 (4.0)	**75 (23)**
Buildings (sprinklers, fire rated)	10 (3.0)	5 (1.5)
Building openings or air intakes	**24 (7.3)**	**75 (23)**
Flammable and combustible liquid storage, vents or fill ports	10 (3.0)	50 (15)
Parking from fill concentrations on bulk storage	13 (4.0)	25 (7.6)
Class 1 Division 2 area diameter	15 (4.6)	15 (4.6)
Maximum bulk storage equipment dimension with lot lines	54 (16)	40 (12)
Minimum bulk storage equipment dimension with lot lines	49 (15)	40 (12)
Maximum bulk storage dimension with separation distances	78 (24)	123 (37)
Minimum bulk storage dimension with separation distances	68 (21)	123 (37)
Reference Area: bulk storage equipment with lot lines	2646 ft^2 (246 m^2)	1600 ft^2 (149 m^2)
Reference Area: storage with separation distances	**5304 ft^2 (493 m^2)**	**15129 ft^2 (1406 m^2)**
Note: Add 5 feet (1.5 meters) for vehicle protection on vehicle facing sides of equipment		

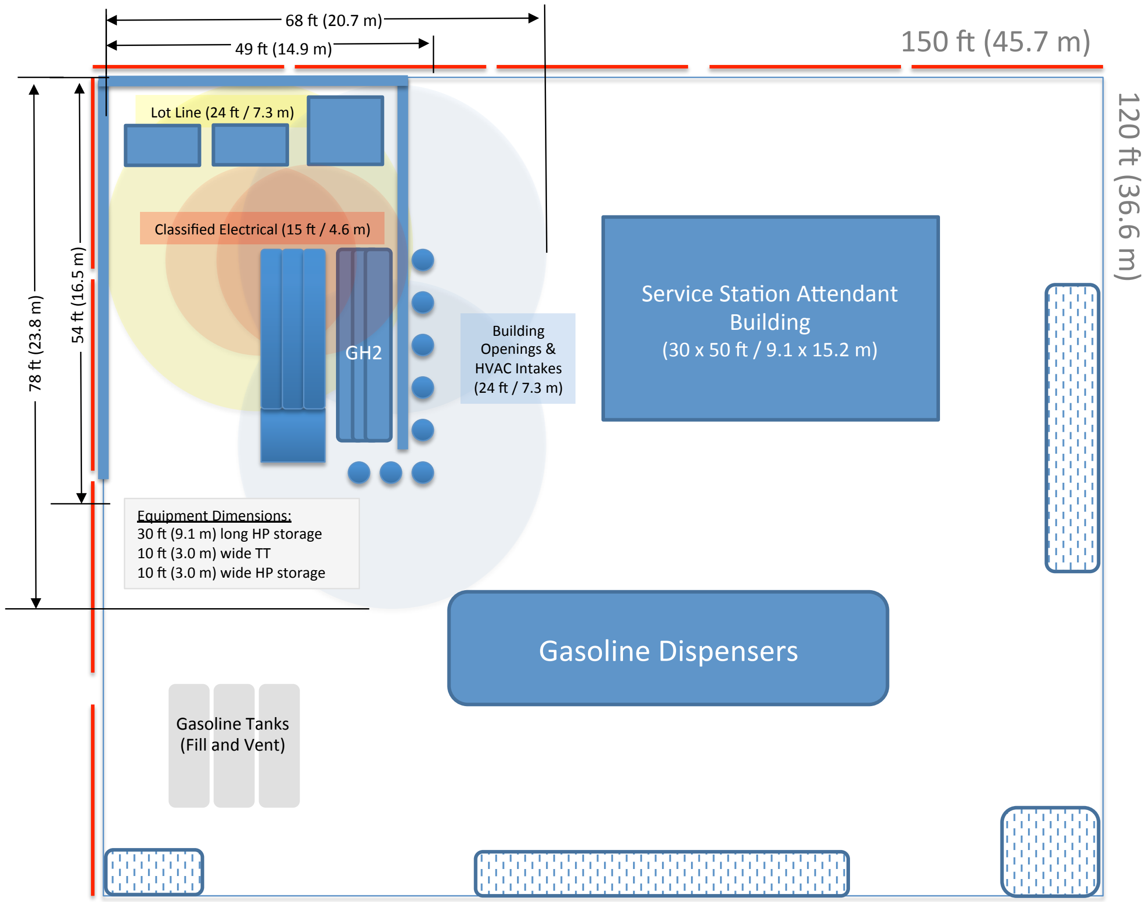


Figure 1 - GH2 reference station: 100 kg GH2 storage, 3 bank cascade and tube trailer with 1 compressor and associated pre-cooler equipment (70 kg/day capacity, 1 dual hose dispenser); 18,000 ft^2 (672 m^2) station site with 5,500 ft^2 (11 m^2) of open space.

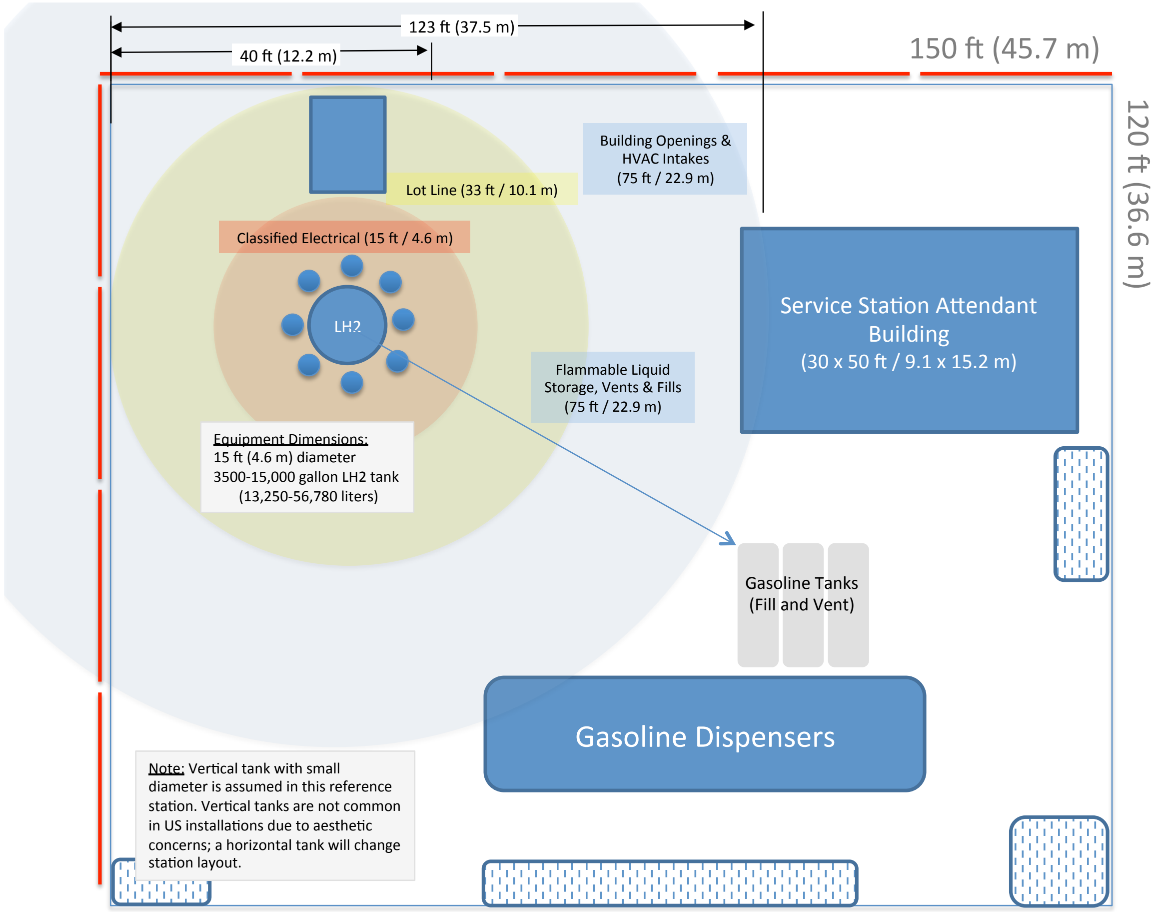


Figure 2 - LH2 reference station: 3500-15,000 gallons (13,250-56,780 liters) (910-1300 kg) LH2 storage (200-300 kg/day capacity, 1-2 dual hose dispensers); 18,000 ft^2 (1,672 m^2) station site with 15,000 ft^2 (1,394 m^2) of open space.

3.2. Comparison of Reference Station Designs to Actual Sites

The reference stations provide a basis for evaluating an existing site for accepting hydrogen based on available area. A systematic process was developed to quickly evaluate existing retail gasoline fueling station sites for hydrogen integration. This process utilized the CEC draft Program Opportunity Notice (PON) from October 2013 and Google Maps to determine the site size and estimated available area. The process used for evaluation was:

1. Determine location from PON
2. Capture location details and images
3. Determine the lot size in square feet
4. Determine the largest possible area available on the site
5. Address the following two *yes/no* questions, based on available area and expert judgment:
    a) Is the site ready for hydrogen installation in the current configuration? (H2 ready)

b) Is it possible to install hydrogen with configurational changes? (H2 possible)

An example is illustrated in the following figures.

Step 1: station locations are indicated with small dots in the draft PON maps provided as an appendix to the PON, Figure 3. A handful of dots were taken as samples of the location and numbered. The following example uses #2: the western-most station in a series of stations along Hollywood Blvd.

Step 2: images of the station are captured from Google Maps (http://maps.google.com) to enable the expert judgment of the integration of the space. Images of all stations evaluated are provided in Appendix A. Figure 4 shows the images captured for this station. It is immediately clear that this station is located on the corner of two arterial roads with an adjacent alley or side road. A large tree covers one side of the lot where there appears to be the filling ports for the underground gasoline storage tanks. The convenience store is located on the north side of the lot and the fueling pump island is in the center of the lot. A large space, currently used for parking is located on the east side of the lot.

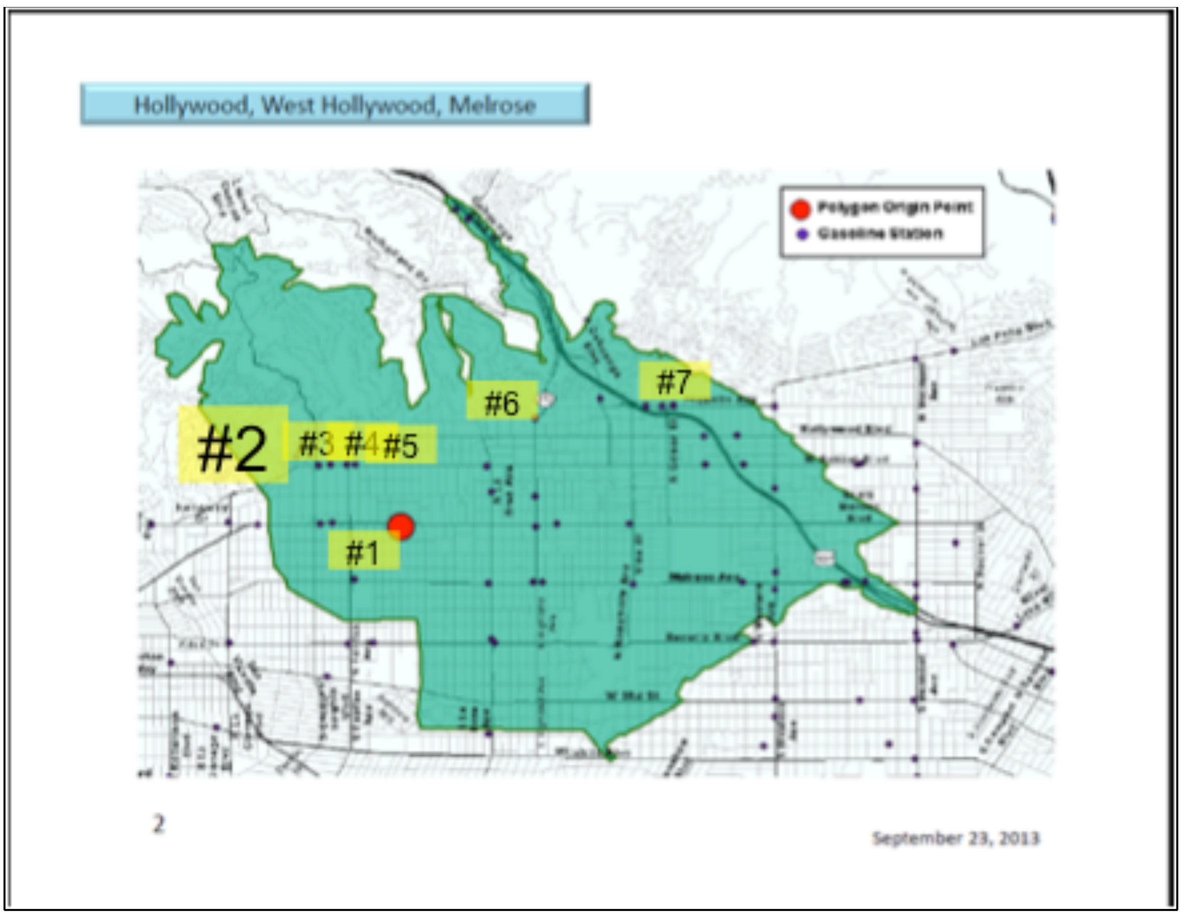


Figure 3 - California Energy Commission-preferred location: Hollywood, West Hollywood, Melrose

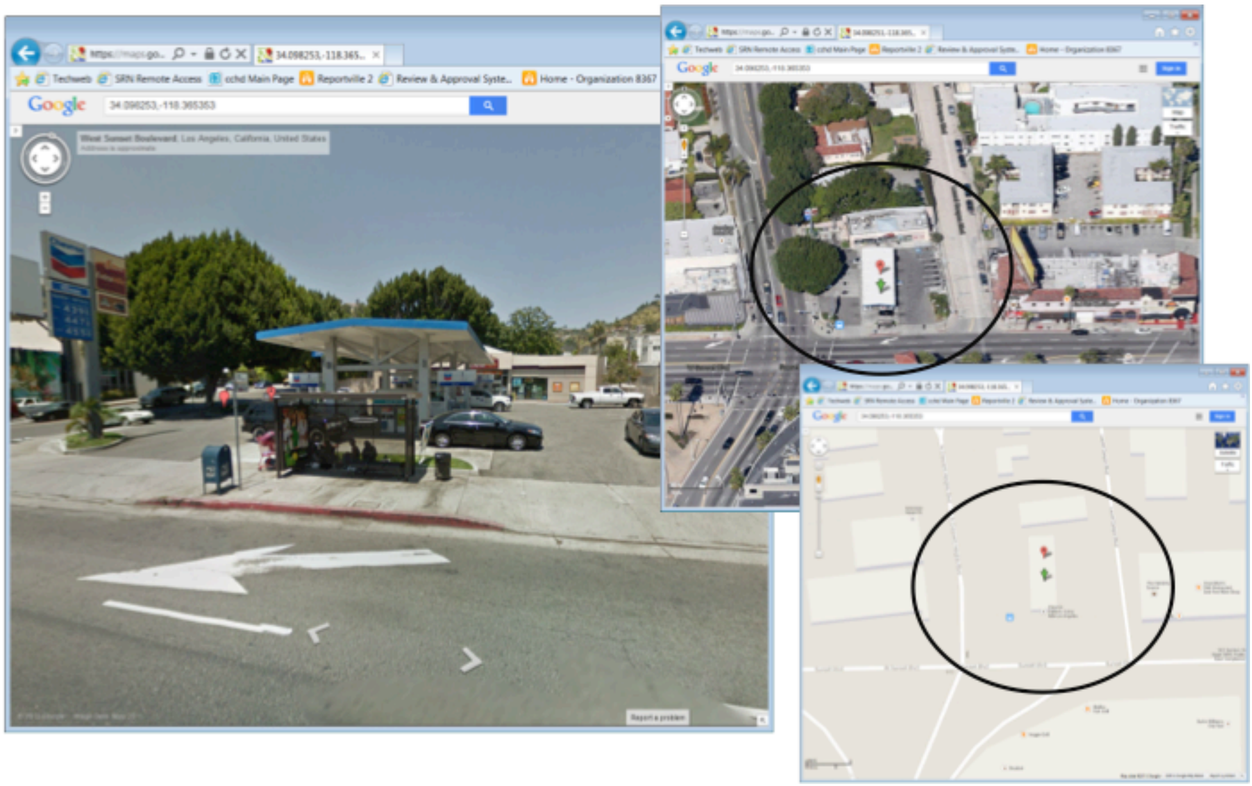


Figure 4 - Hollywood #2: image from Google Maps

Step 3: the site is analyzed for size. This is done using the object drawing function in Microsoft PowerPoint (MS PPT) and counting the pixels of a rectangle that covers the site. Several steps are critical to ensure the most accurate estimate of the lot and available space area. The captured image cannot be resized once copied to MS PPT. Second, the rectangle pixel count must be adjusted for each image. For this analysis, each image was captured with the Google Map scale showing a minimum scale of 50ft (15 meters). Once moved to MS PPT, the pixel to feet scale was adjusted for that particular image (a simple linear calculator was used to calibrate each image). From that point, a rectangle drawn on that image should closely resemble actual square footage. The same simple calculator converted pixels to square feet. Figure 5 shows the rectangle used to determine the available space for this station location.

Step 4: for the "Hollywood #2" station, the available space is 3,726 ft^2 (346 m^2).

Step 5 and result: given the available space and requirements of the hydrogen equipment, expert judgment is needed to address the questions of available and potential siting. For example, the distance from the building openings and air intakes might have been sufficient for "Hollywood #2"; however, the available space is only about 29 ft (8.8 meters) wide, allowing cars to access the island from both directions. The GH2 equipment requires 49 feet (15 meters) of width; therefore, this site is determined not ready to accept hydrogen, as well as not possible to accept hydrogen ("no" and "no" to the questions for step 5 of "H2 ready?" and "H2 possible?").

A table summarizing the results for all stations analyzed in this report is provided in the following section.

A second region is shown in Figure 6: the Pasadena location with Pasadena #1 emphasized. This station does have the space to accommodate the GH2 reference station equipment and separation distances with slight overlap of the separation distance onto the existing building. Figure 7 provides the images of the station taken from Google Maps, while Figure 8 shows the equipment drawn to scale with separation distances. In this case, expert judgment is that the Pasadena #1 site can readily accept hydrogen with regard to the NFPA 2 (2011) code requirements.

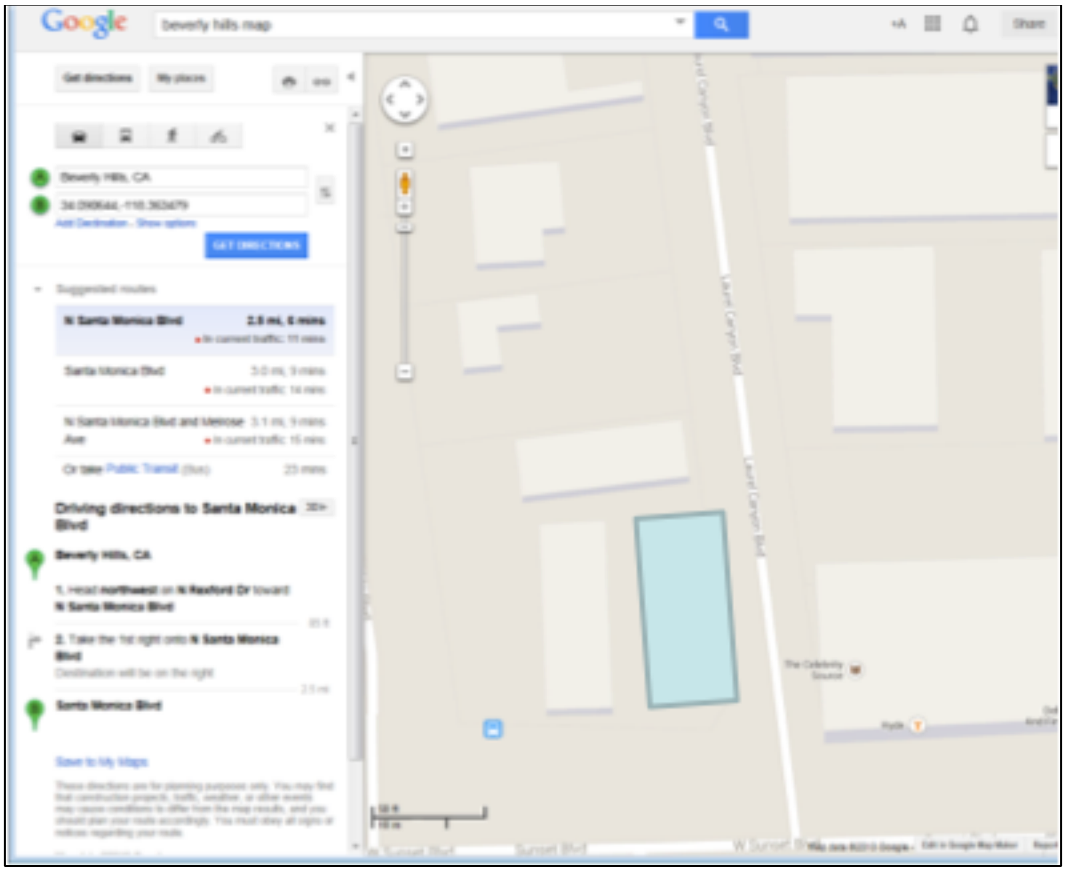


Figure 5 - Image capture and rectangle estimating tool for determining lot size and available space for "Hollywood #2".

Pasadena

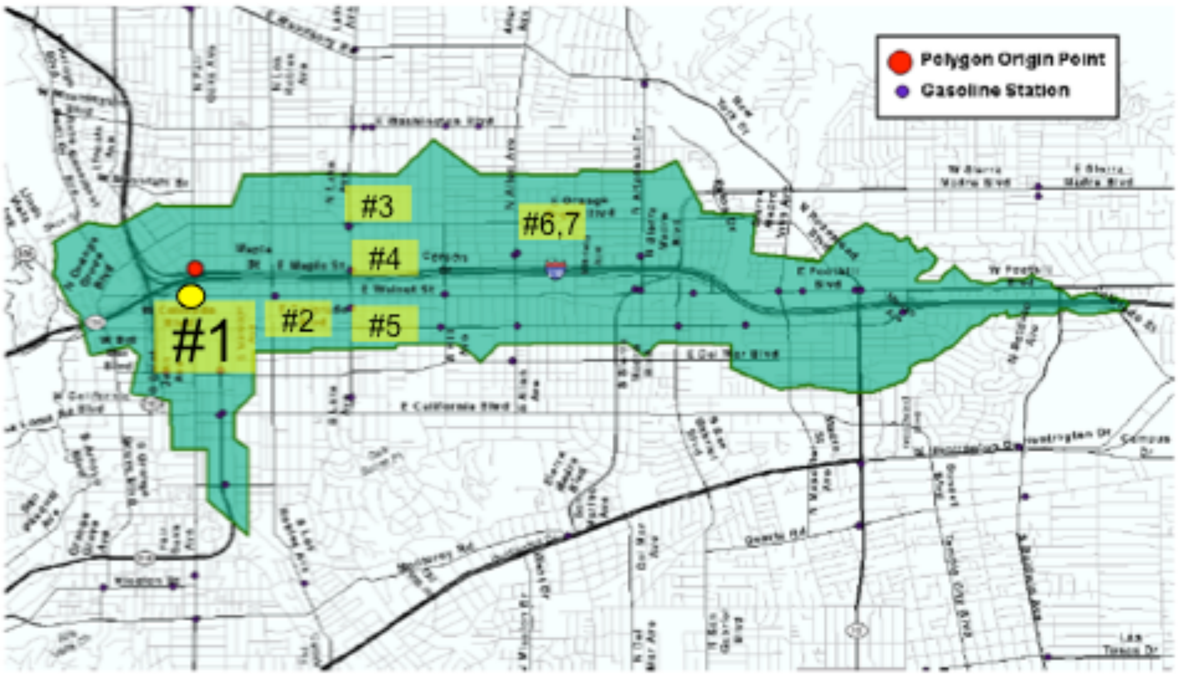


Figure 6 - Pasadena #1 shown on the CEC Pasadena preferred station location map

Figure 7 - Pasadena #1: image captures from Google Maps.

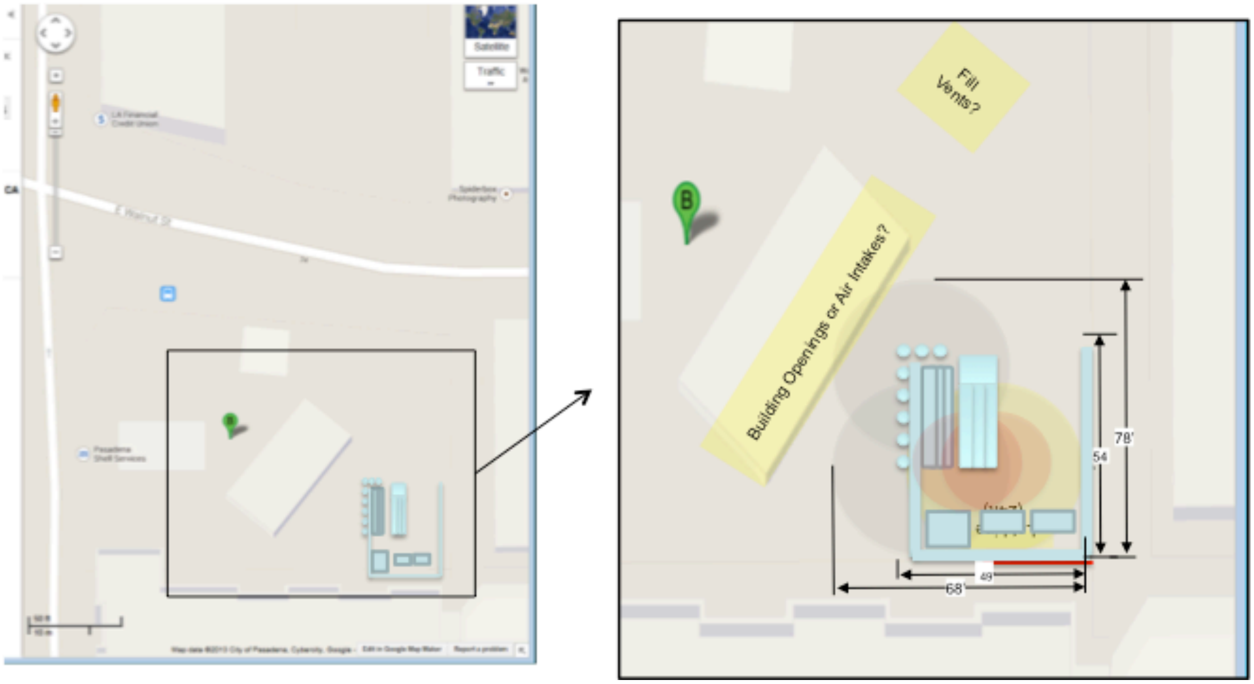


Figure 8 - At left, Pasadena #1 at scale showing the potential location of GH2 equipment in the lower right corner. At right, a closer look at the GH2 equipment, note the slight overlap of the separation distance zone with the building.

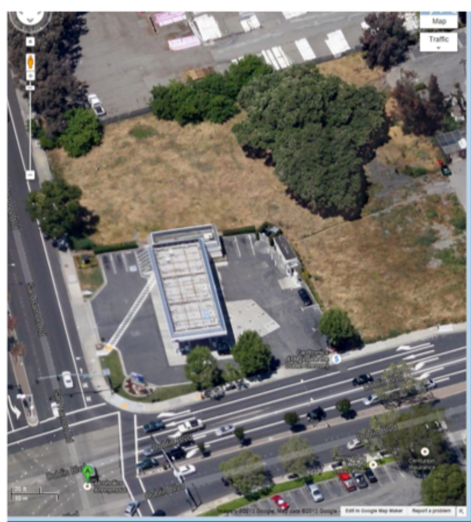


Figure 9 - Dublin #6: example of a site where zoning and use of surrounding lots may affect the viability of hydrogen integration

Table 2 - Results of benchmarking study using NFPA 2 (2011) separation distances.

PON polygon	Number of stations identified	Number of stations analyzed	H2 ready	H2 possible	Total H2 potential
Beverly Hills/Westwood	2	2	0	0	0
Hollywood/West Hollywood	36	7	1	1	2
Pasadena	26	7	3	2	5
San Diego #1	13	7	2	4	6
San Francisco	14	7	0	1	1
Torrance/ Redondo Beach	8	7	0	2	2
Westminster/Huntington Beach	37	15	5	3	8
Berkeley/Oakland	23	11	1	1	2
Dublin/Pleasanton	15	7	2	3	5
Totals	174	70	14	17	31

3.3. Benchmarking Results

The results from analysis of 174 sites provide a preliminary understanding of the overall population of sites ready for hydrogen integration. These results are summarized in Table 2. A detailed statistical assessment of the results is unwarranted at this time. Nevertheless, if the current trend were to hold for the entire population, the number of "Potential" stations appears to be between 18% and 44%[a].

The reader is cautioned from drawing any further conclusions from this small sample regarding the overall number of gasoline station sites that can readily accept hydrogen statewide or nationwide. The reasons for caution include:

1) Gasoline station lot sizes vary greatly – many of the ideal areas for hydrogen early adoption also contain a disproportionate number of older generation gasoline stations. Several of the analyzed regions include sites that are located on triangle lots or very small lots, particularly in urban areas. These sites would not likely be approved under the current codes for gasoline, thus expectations for hydrogen should be tempered. This anomaly stands to reason as the Los Angeles area, particularly the hydrogen early-adopter areas, developed during an era where small businesses opened corner gasoline stores, unlike the newer suburbs or other regions of the nation which tend to have newer, larger retail gasoline stations.

[a] Simple arithmetic estimate of the range based on either: the number of possible stations doesn't grow after analysis of all 174 stations (31/174 = 18%) or the trend holds and the number of readily integrated sites grows with the population at the measured rate (31/70 = 44%)

2) Code application is different than code analysis – in the United States, the local code official often has much of the authority to amend or waive requirements in the code. The siting process may occur with an assessment of the zoning for the adjacent lots. The analysis presented here does not cover such considerations and is strictly based on the available space on the existing lot. Figure 9 shows an example of such a situation. This gasoline station is assessed as "not ready" and "not possible" for hydrogen siting as the lot is not large enough to readily accept hydrogen. However, if the surrounding property were included in the planning, through lease or purchase, this site might be capable of hosting a LH2 station, with its large separation distance footprint, as well as capable of hosting a GH2 station.
3) Existing gasoline stations may not be the only locations for hydrogen fueling. For instance, large parking lots have been suggested as alternate locations. These "expanded site populations" are discussed in a later section.

Given the variability of the gasoline stations, as well as alternative hydrogen sites such as parking lots or other facilities, it is recommended that sites be evaluated individually for hydrogen readiness. To facilitate this effort, a database of 3000-5000 stations would need to be developed. For a study of the 175,000+ gasoline stations nationwide, a statistical approach is required and a large, accurate database will facilitate a better national estimate. Such an approach should ensure that variables such as regional fueling sites, land costs, state and local code-approaches are controlled. A comprehensive national analysis may prove beneficial to national planning efforts already underway.

4. METRIC APPLICATION TO PREVIOUS PROGRAM INVESTMENTS

The results from benchmark effort indicate an 18% to 44% likelihood that an existing gasoline station can readily accept hydrogen, based only on lot size. This section explores the impact of previous work supported by the US DOE FCTO's Safety Codes & Standards (SCS) program elements that lead to the development of risk-informed separation distances in NFPA 2.

A comparison of the separation distances of 2005 edition of NFPA 55 and the 2011 edition of NFPA 2 is summarized in in Table 3 and provides some insight into the changes made between the two codes. Before comparing the evolution of separation distances in the NFPA code, two important misrepresentations of the results are clarified:

1) The SCS program did not conduct research to reduce the separation distances; the research effort was focused on, and succeeded in, changing the code development approach from an "expert opinion-based process" to a "risk- informed process". In so doing some of the separation distances were reduced and some were expanded.
2) Separation distances may not be the only technical barrier to widespread deployment of hydrogen with respect to safety codes and standards, therefore separation distance reduction should not be the only focus. It is for this reason that the proposed metric focuses on increasing the population of sites that can readily accept hydrogen rather than narrowly focusing on separation distances.

The comparison of NFPA 55 (2005) and NFPA 2 (2011) separation distances revealed that the separation distance 'footprint' was much larger for NFPA 55 (2005). Of the 70 stations evaluated in the benchmarking effort, none of the existing gasoline stations would readily accept hydrogen under the NFPA 55 (2005) requirements. Therefore, the proposed metric, *number of fueling stations that can readily accept hydrogen* increased from 0% to a range of 18-44% for existing gasoline stations. This increase is directly attributable to the efforts of the US DOE FCTO SCS program element.

Table 3 - Comparison of separation distances in NFPA 2 (2011) and NFPA 55 (2005) for GH2.

Separation Distance Comparison			
Fuel system descriptions: GH2 – 12,500 psi (862 bar) storage, 100 kg, 0.4 in (10 mm) ID tubing with a barrier wall Expert opinion: NFPA 55 (2005) Science-based: NFPA 2 (2011), NFPA 55 (2010, 2013)		Expert opinion GH2 ft (m)	Science-based GH2 ft (m)
Group 1	Lot lines	0 (0)	**24 (7.3)**
	Air intakes	**50 (15)**	**24 (7.3)**
Group 2	Ignition sources (such as open flames and welding)	0 (0)	24 (7.3)
	Exposed persons other those servicing the system	*nd*	13 (4.0)
	Places of public assembly	**50 (15)**	*nd*
	Parked cars	15 (4.6)	13 (4.0)
	Public sidewalks and parked cars	15 (4.6)	*nd*
Group 3	Un-openable openings in building and structures	*nd*	10 (3.0)
	Not above any part of the system	10 (3.0)	*nd*
	Above any part of the system	25 (7.6)	*nd*
	Overhead utilities (including electric power, building services, or hazardous materials piping systems)	*nd*	10 (3.0)
	Distance to overhead electric wire of electric trolley, train or bus line (horizontal distance to vertical plane of electric wire)	50 (15)	*nd*
	Required area for separation distance (based on table alone)	3780 ft^2 (351 m^2)	5304 ft^2 (493 m^2)
	Required area for sampled installations (sites requiring lot line separation of 15 m)	12480 ft^2 (1159 m^2)	5304 ft^2 (493 m^2)
Notes: *nd* = not defined			

5. FUTURE WORK

There are many opportunities to use the proposed metric, *number of fueling stations that can readily accept hydrogen*, to improve the value of existing projects and demonstrate the potential impact of future work. This section provides a few examples.

LH2 separation distances – a barrier to market development is the ability to locate large quantities of hydrogen on existing fueling sites. As demonstrated in the benchmarking exercise, LH2 systems face significant siting challenges; none of the 70 analyzed sites could readily host LH2, although the site shown in Figure 9 might be capable if the surrounding lots were used. The lack of data and risk-informed analysis for LH2 prevents the code development committee from moving forward with revisions to the requirements based on scientific results. The development and validation of LH2 behavior models and the performance of risk assessments necessary for the risk-informed approach could be measured against this metric.

Mitigation strategies and engineering controls – the use of mitigation strategies and engineering controls could also be measured using the proposed metric. The application of wide-area sensors, for example with intelligent safety control systems, could demonstrate a reduced risk based on the incident mitigation that such sensors provide. The benefits of the sensor research could be determined based on the projected number of sites whose hydrogen feasibility is impacted by the implementation of these sensors. Many other mitigation strategies can also be assessed, such as better quantification of the behavior of walls.

Component and systems standards development – fueling systems deployed in the field do not currently meet a standard suite of product standards. Many of these standards have only recently been published which means that products certified to these standards are not yet available. Once these standards are implemented, there will be a stronger acceptance by the public safety community that the minimum requirements provide sufficient protection. An analysis effort which aggregates the entire suite of requirements and identifies the redundant safety margins at each level (component, system, and site) could reveal the comprehensive margin of safety for the code compliant system. Recommendations for the reduction of redundant safety margins could be measured using the proposed metric.

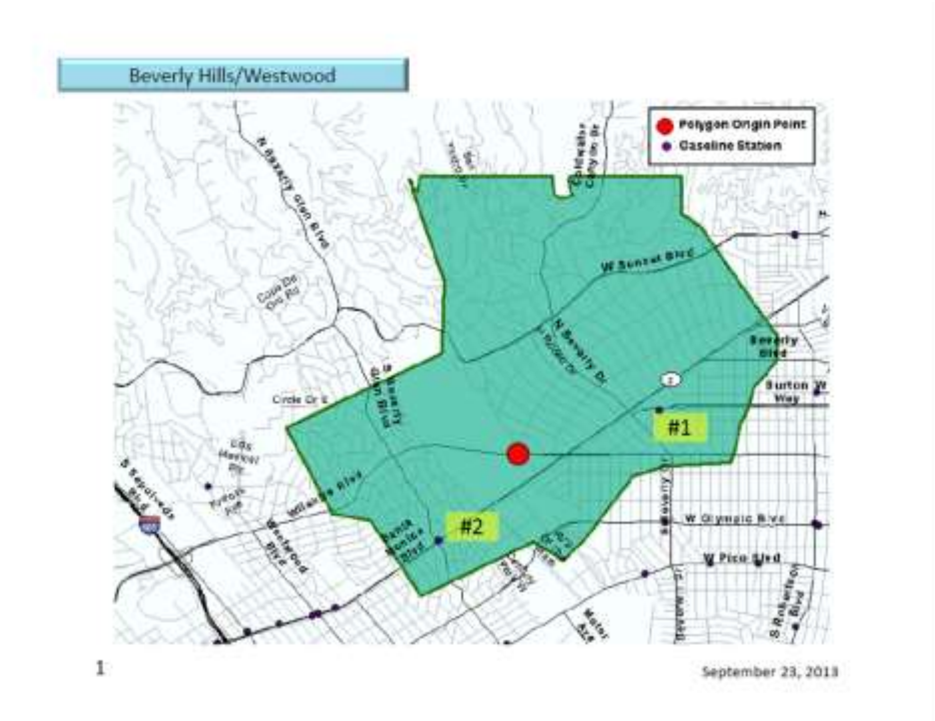
Data collection and analysis – the risk-informed process accuracy is improved by specific and reliable data sources. Projects including the collection and analysis of field data and field incidents for hydrogen fueling systems could have a large impact on the proposed metric. This could be both (i) direct with modification in the application of code requirements or (ii) indirect through the improvement of risk-informed analysis for prescriptive requirements.

6. REFERENCES

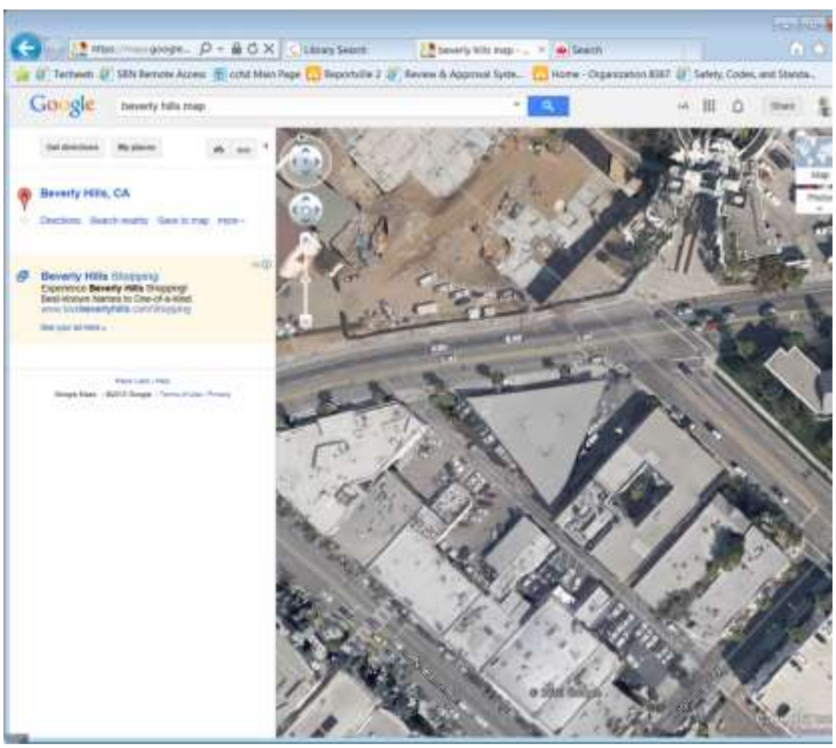
1. Technical Plan – Safety, Codes and Standards, 2012. U.S. Department of Energy (DOE) Fuel Cell Technologies Program (FCT). https://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/safety_codes.pdf
2. NFPA 2, Hydrogen Technologies Code, National Fire Protection Association Std., 2011.
3. J. LaChance, "Risk-informed separation distances for hydrogen refueling stations," International Journal of Hydrogen Energy, vol. 34, no. 14, pp. 5838–5845, 2009.
4. J. LaChance, W. Houf, B. Middleton, and L. Fluer, "Analyses to support development of risk-informed separation distances for hydrogen codes and standards," Sandia National Laboratories, Albuquerque, NM, Tech. Rep. SAND2009-0874, March 2009.
5. J. LaChance, A. Tchouvelev, and J. Ohi, "Risk-informed process and tools for permitting hydrogen fueling stations," International Journal of Hydrogen Energy, vol. 34, no. 14, pp. 5855–5861, 2009.
6. W. Houf and R. Schefer, "Predicting radiative heat fluxes and flammability envelopes from unintended releases of hydrogen," International Journal of Hydrogen Energy, vol. 32, no. 1, pp. 136–151, 2007.
7. PON-13-606, Hydrogen Fuel Infrastructure. California Energy Commission, 2012. http://www.energy.ca.gov/contracts/PON-12-606/.

APPENDIX A: CALIFORNIA BENCHMARKING REFERENCES

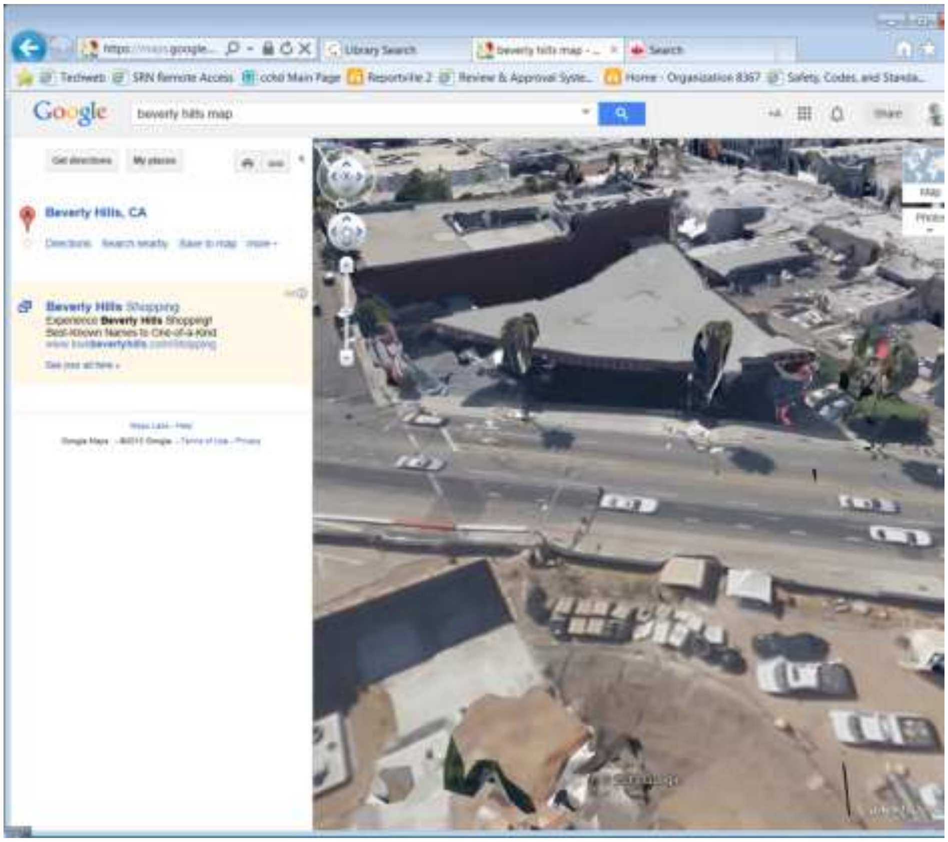
CEC Primary Location Beverly Hills (2 stations)



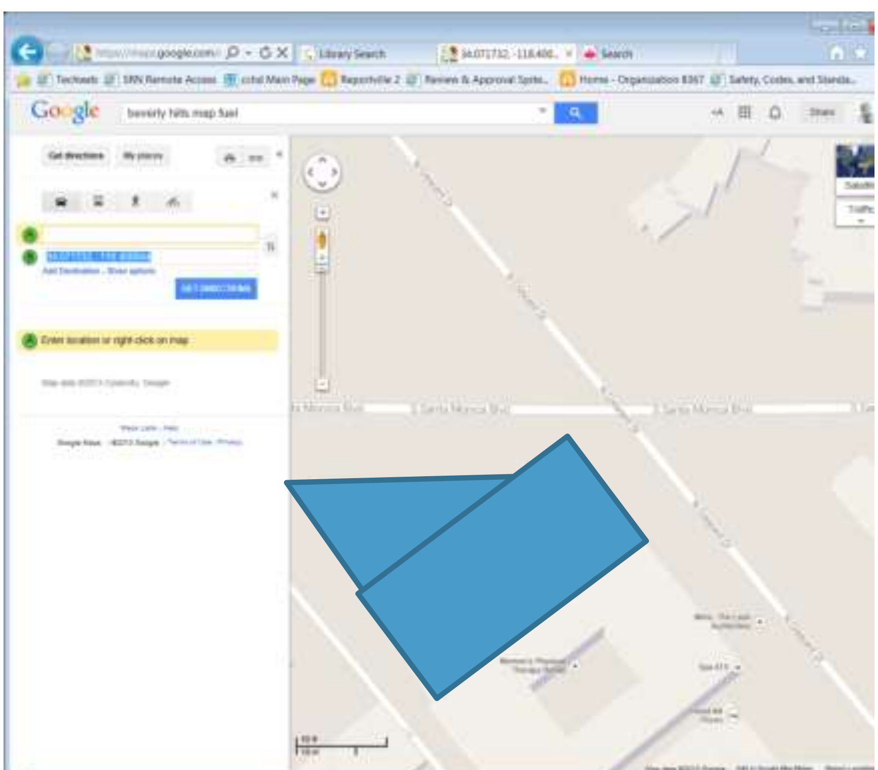
Beverly Hills #1



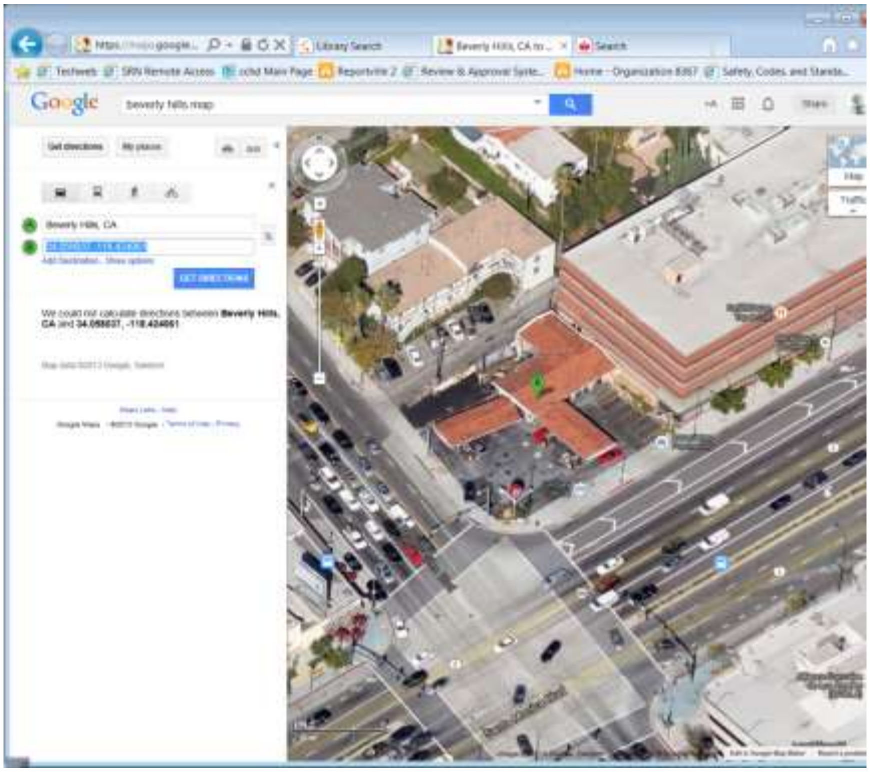
Beverly Hills #1



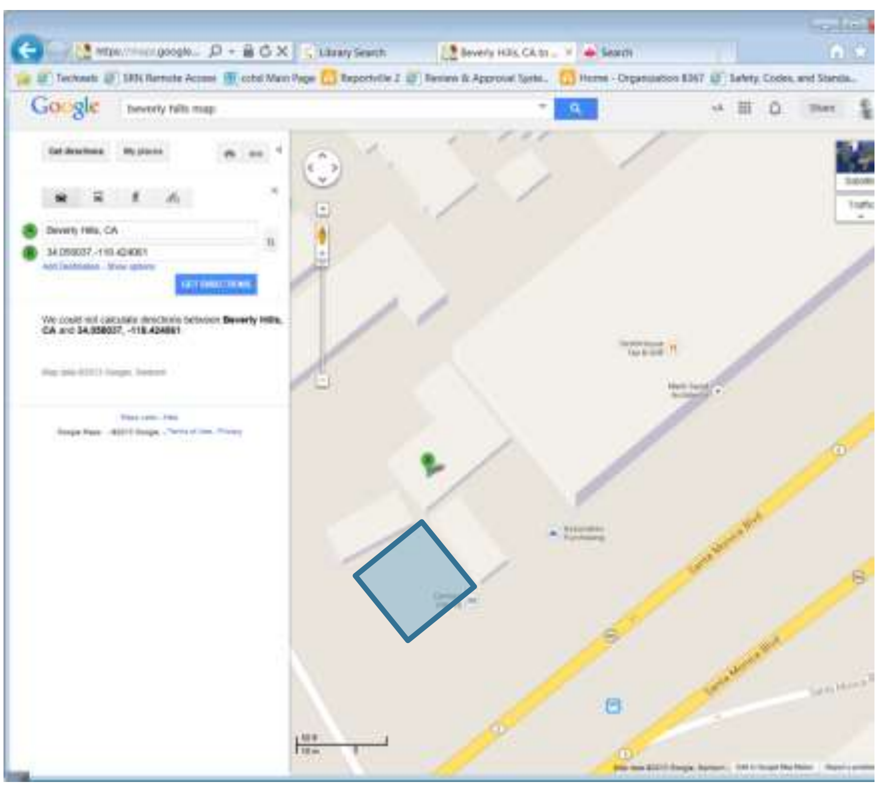
Beverly Hills #1



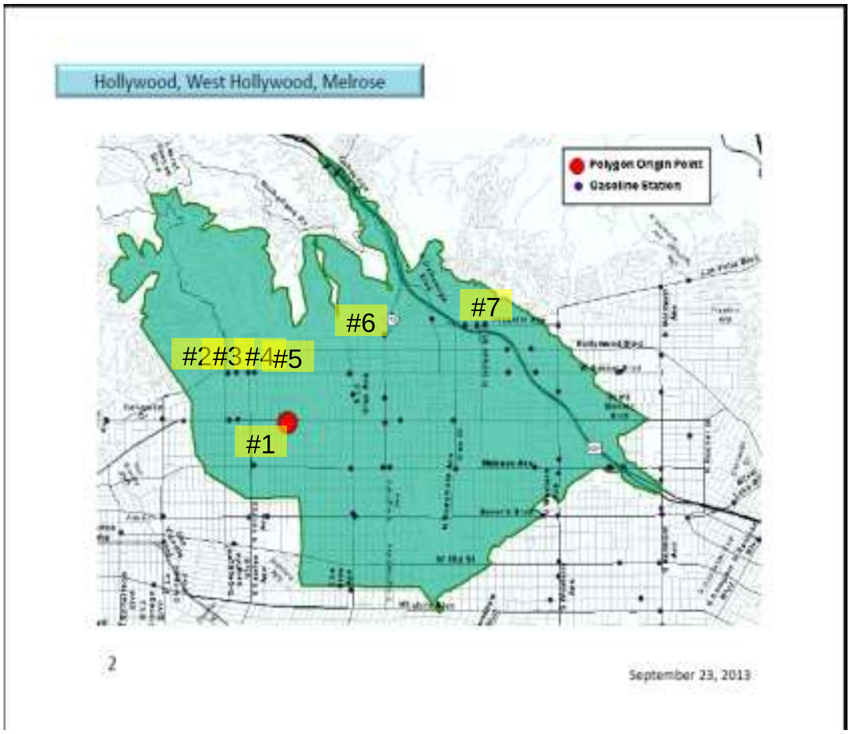
Beverly Hills #2



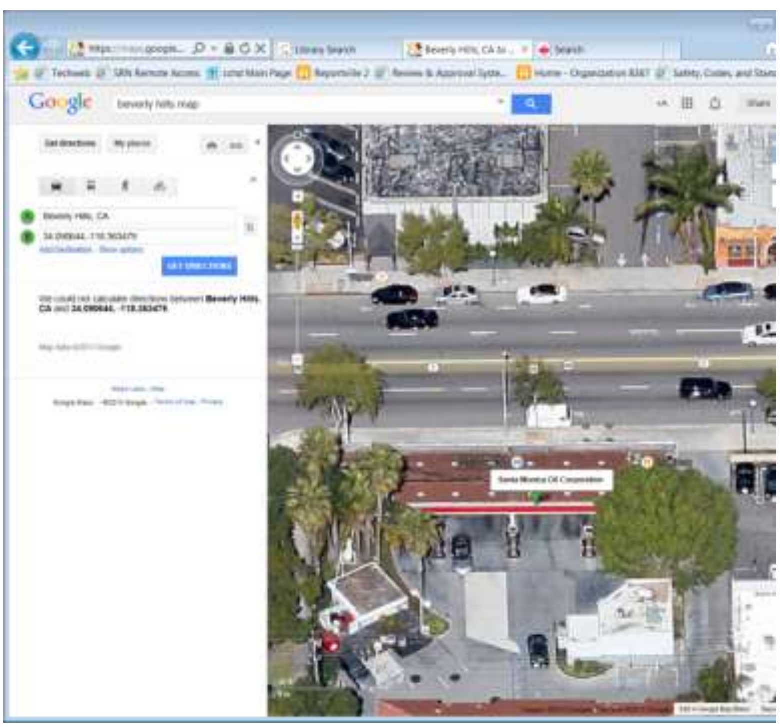
Beverly Hills #2



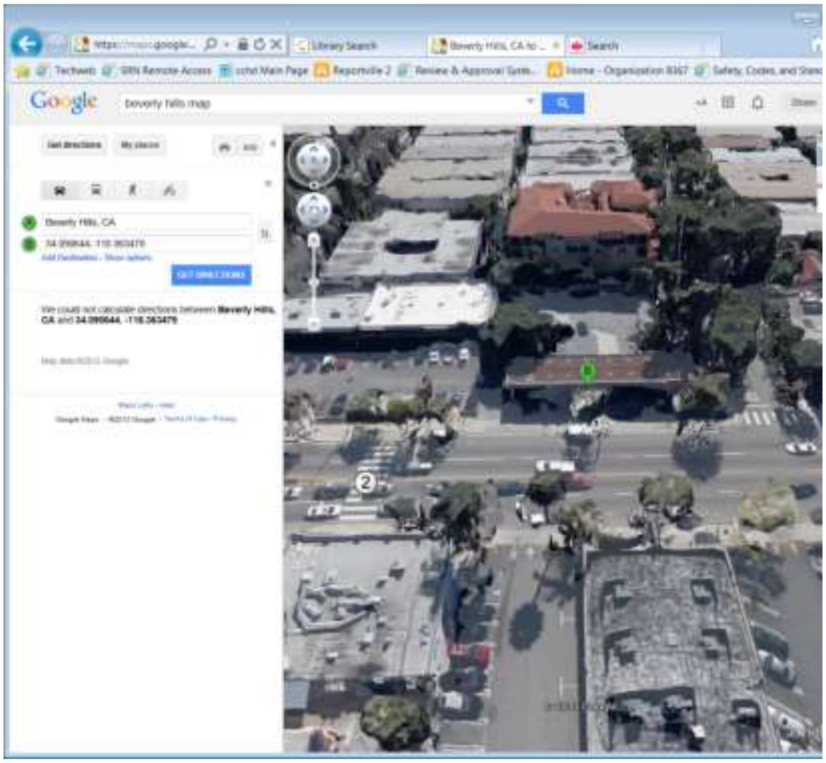
CEC Primary Area
Hollywood (36 stations)



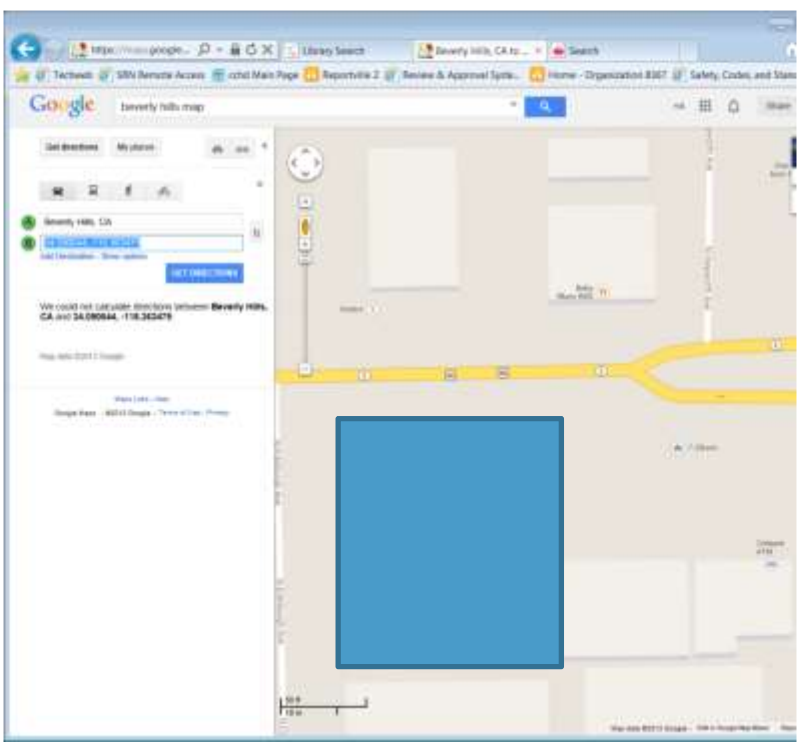
Hollywood #1



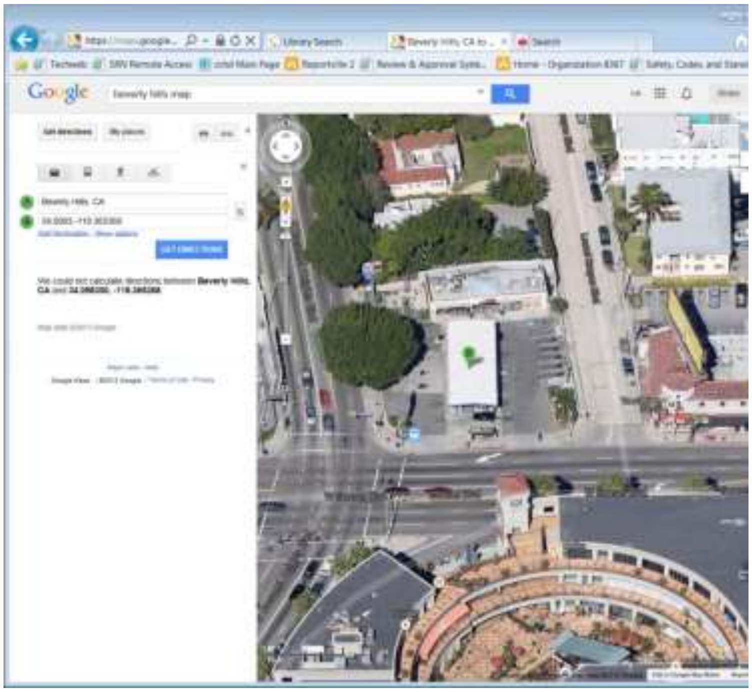
Hollywood #1



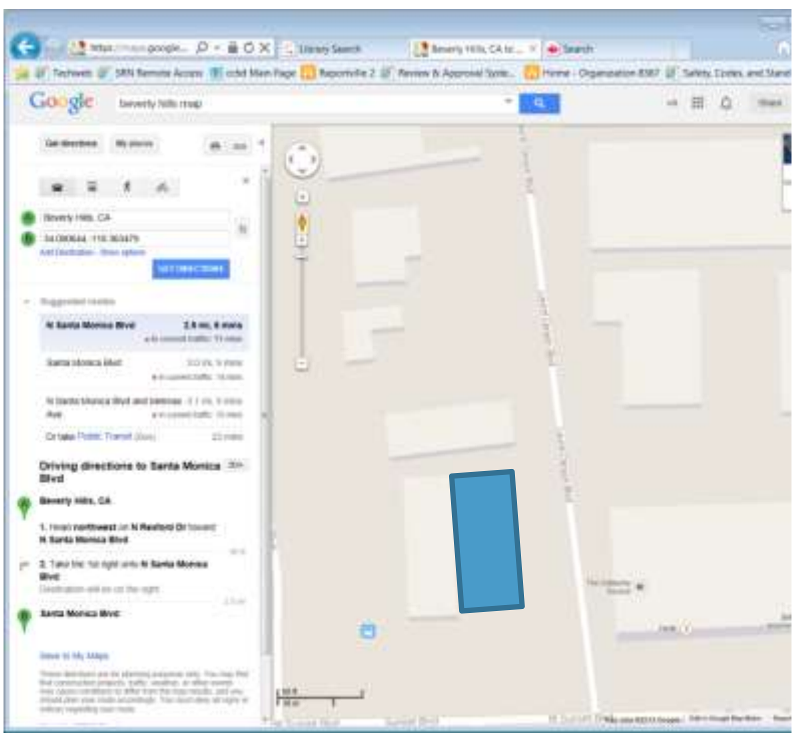
Hollywood #1



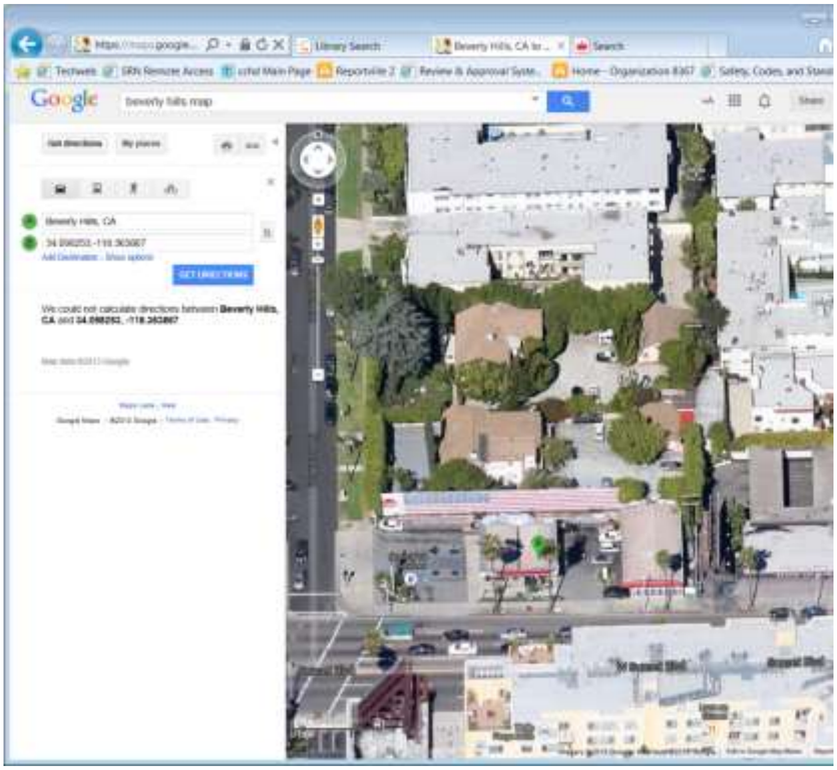
Hollywood #2



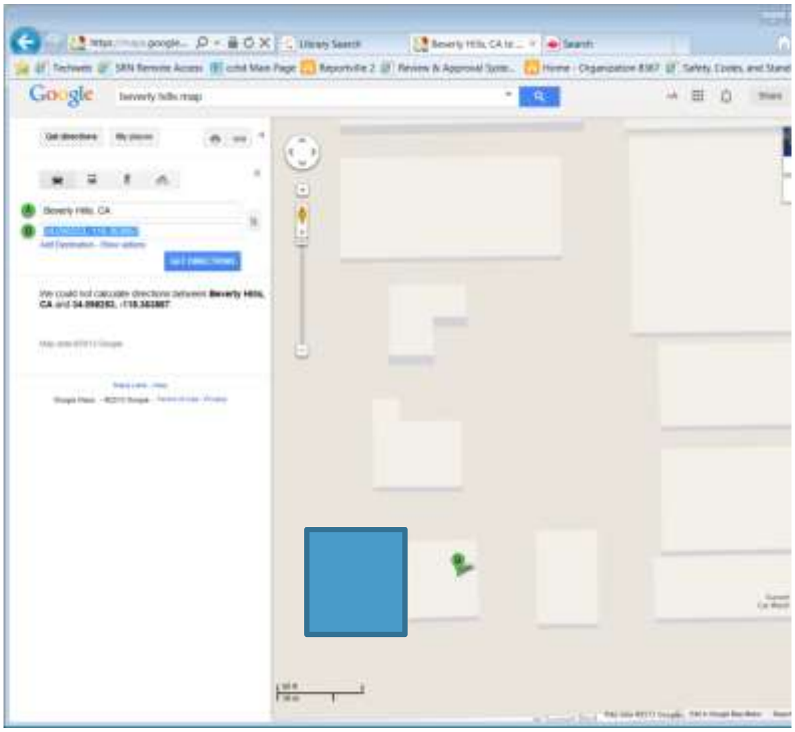
Hollywood #2



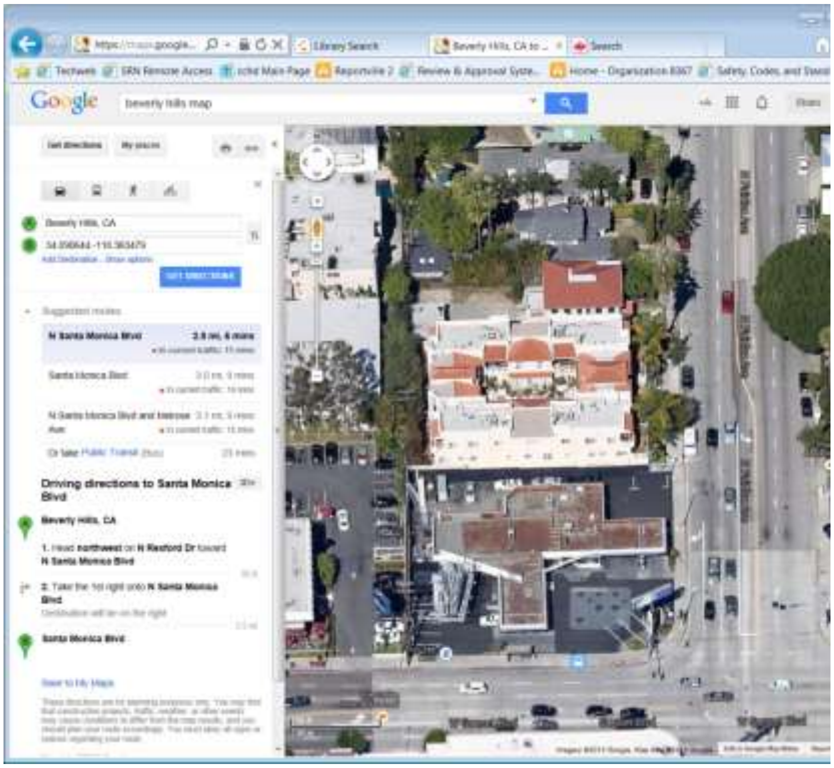
Hollywood #3



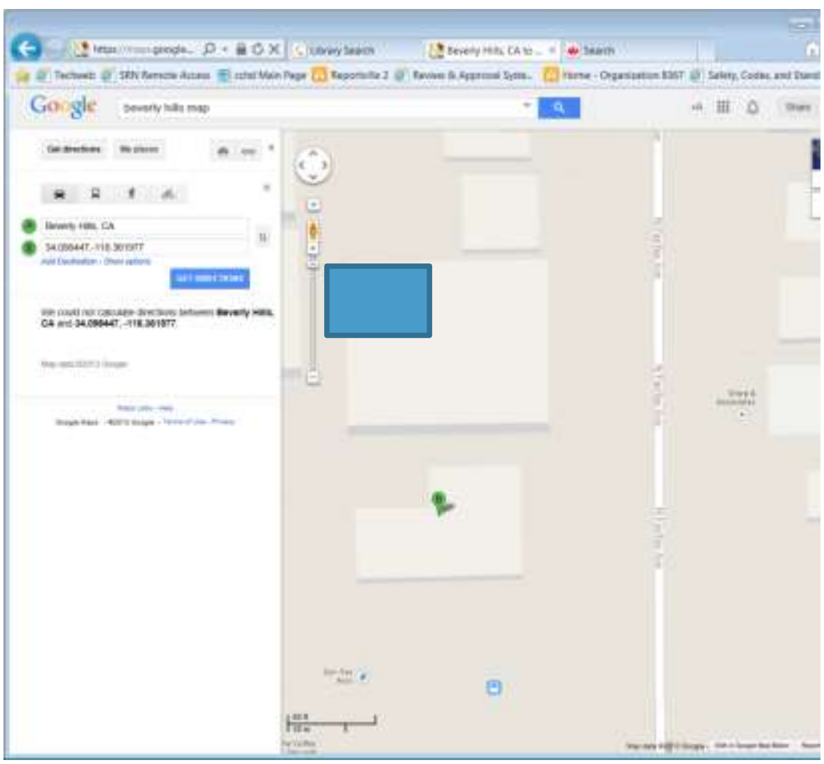
Hollywood #3



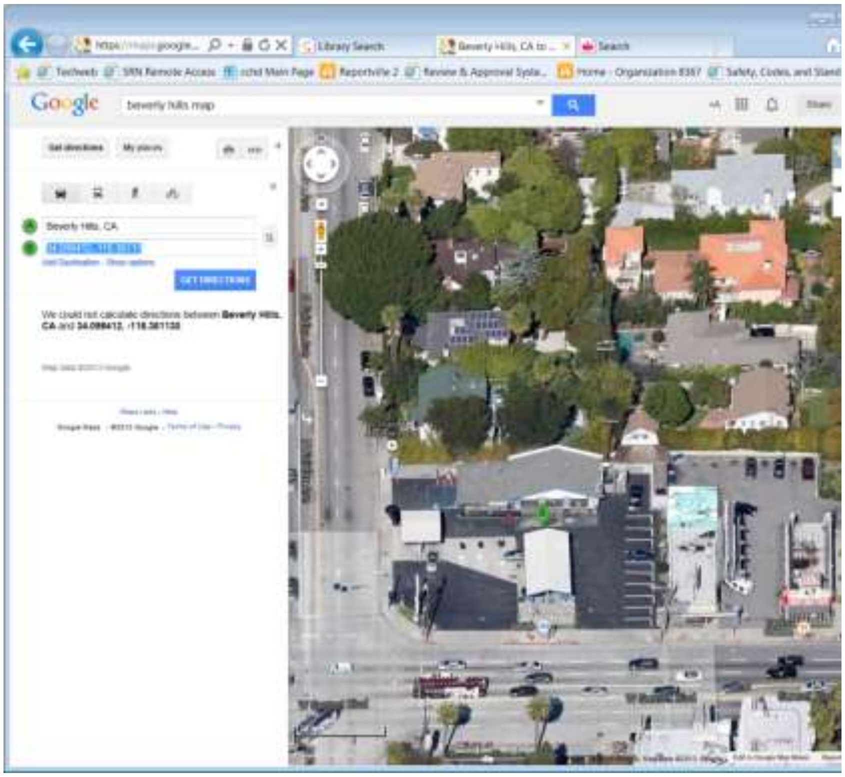
Hollywood #4



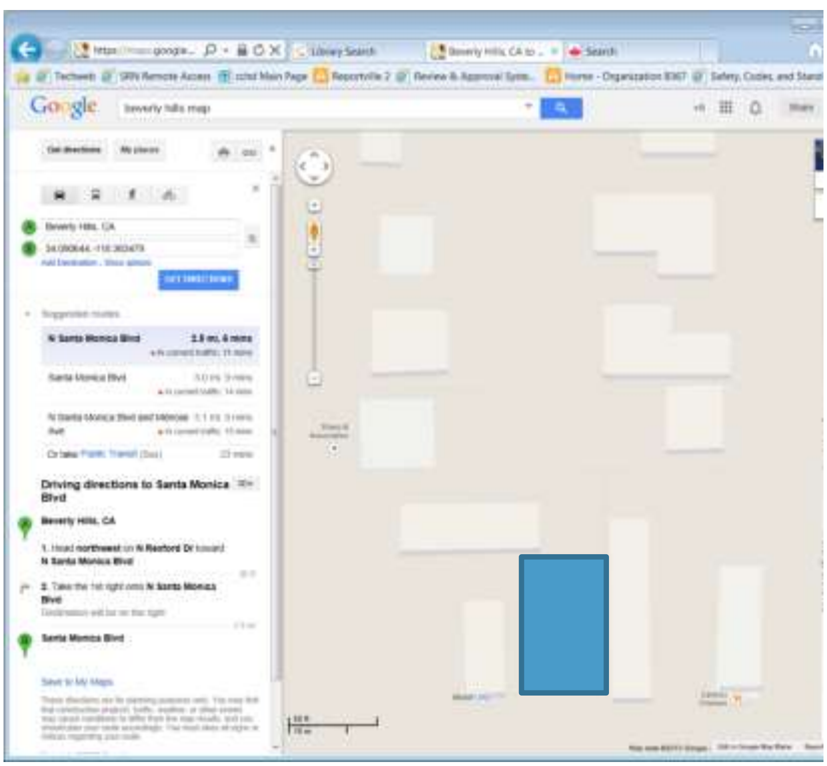
Hollywood #4



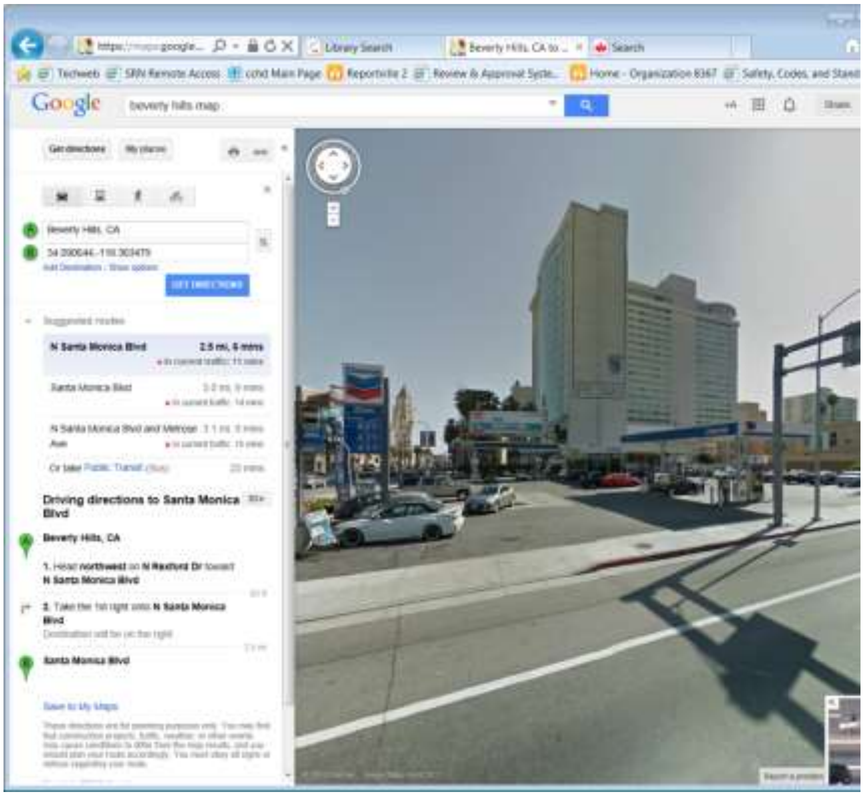
Hollywood #5



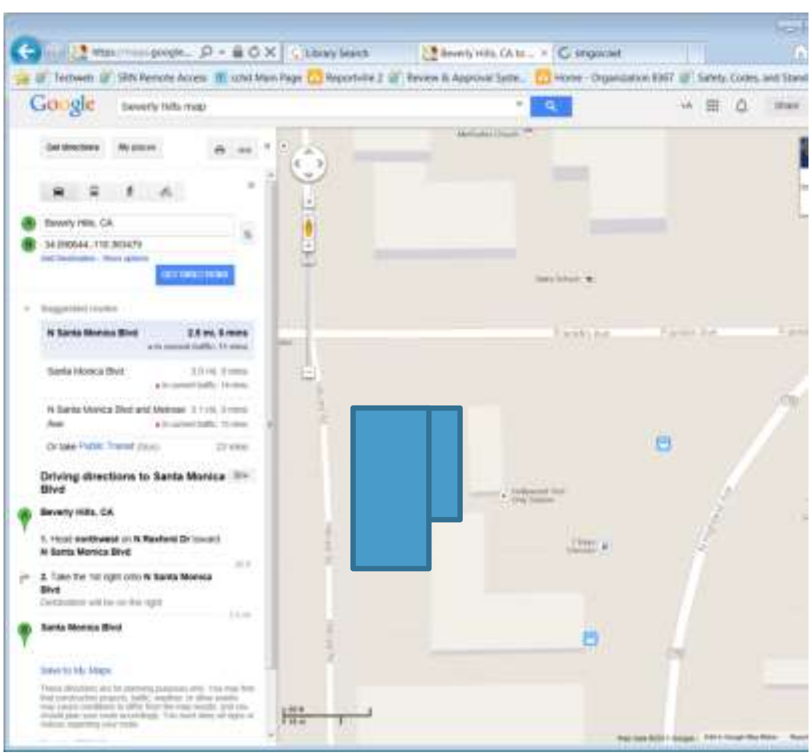
Hollywood #5



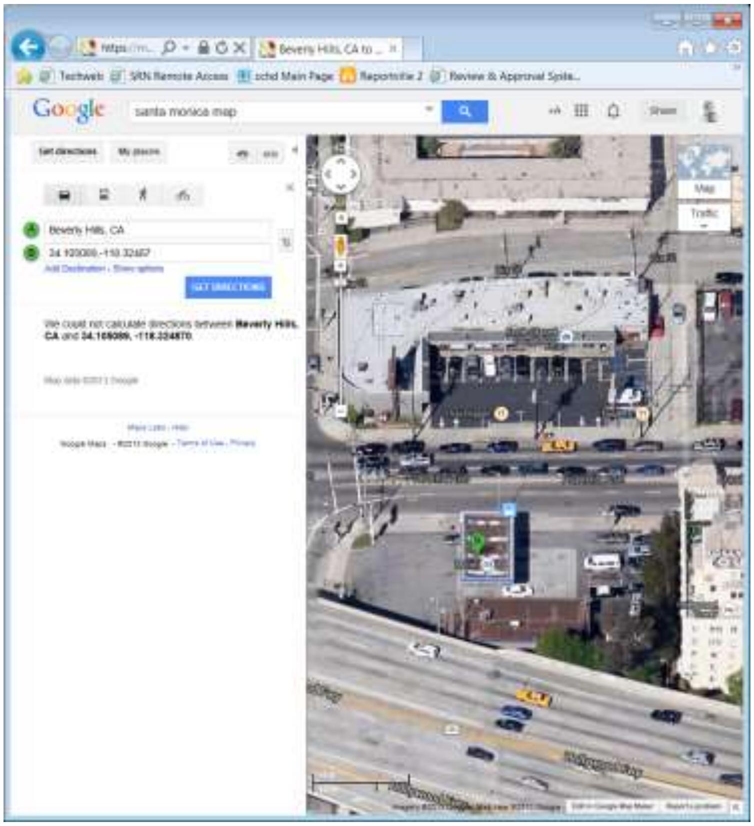
Hollywood #6



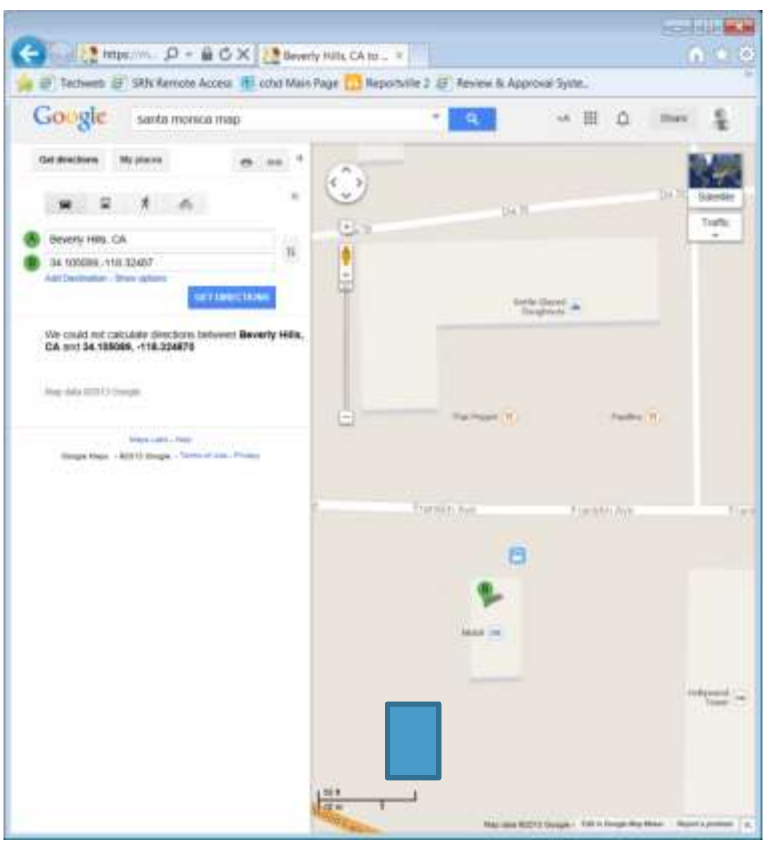
Hollywood #6



Hollywood #7

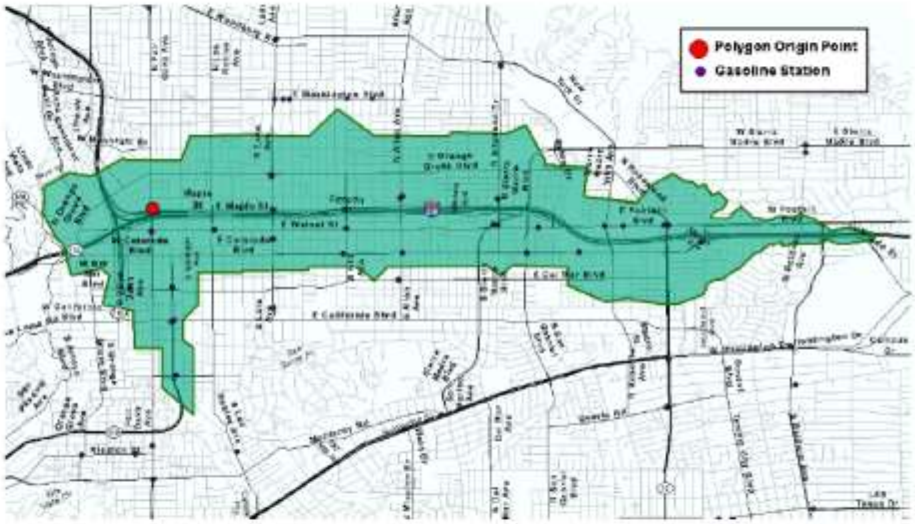


Hollywood #7



CEC Primary Area
Pasadena (26 stations)

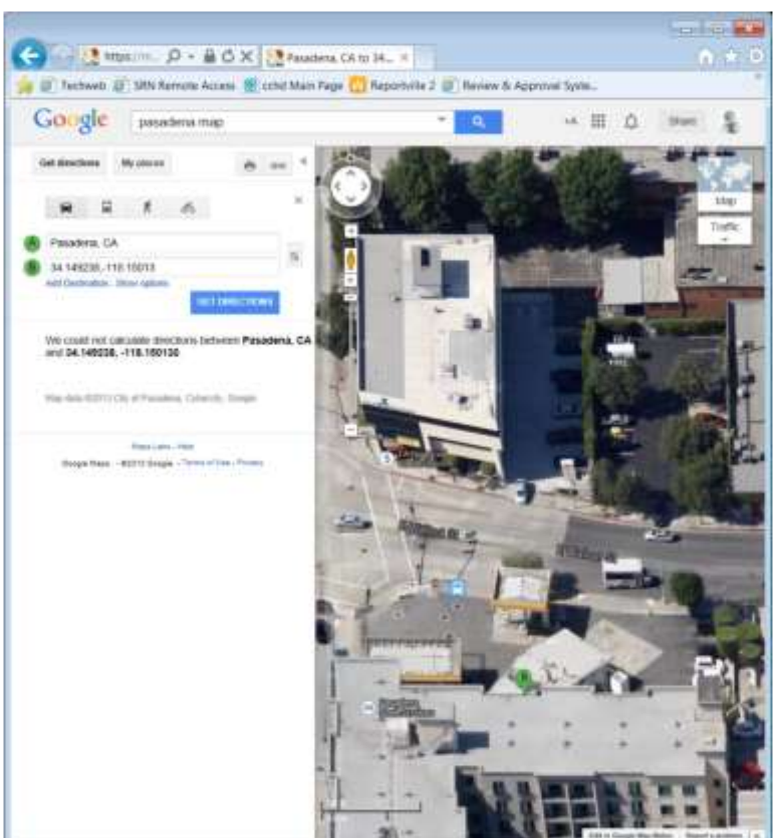
Pasadena



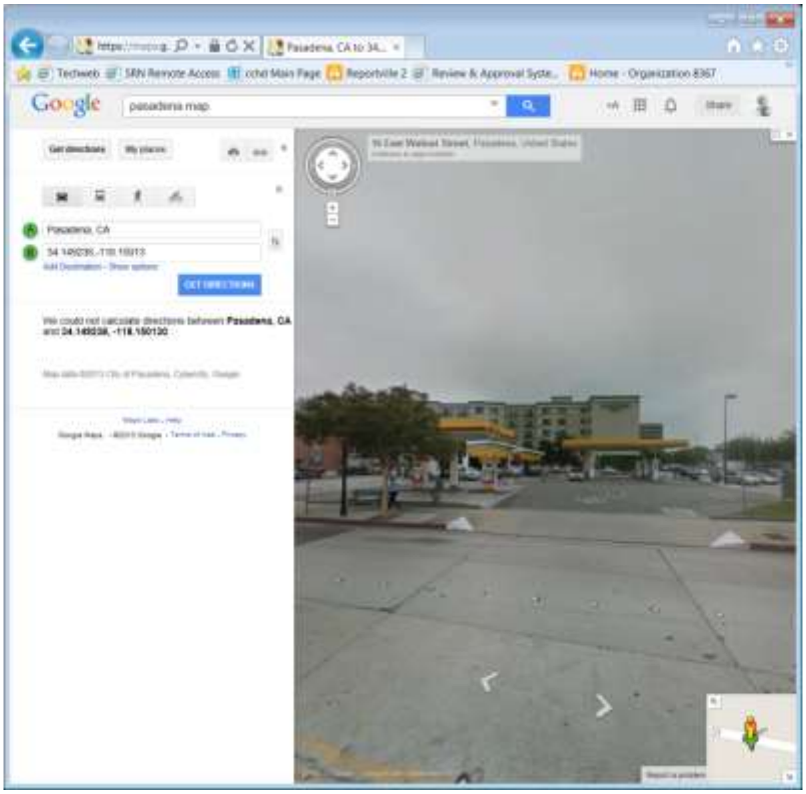
3

September 23, 2013

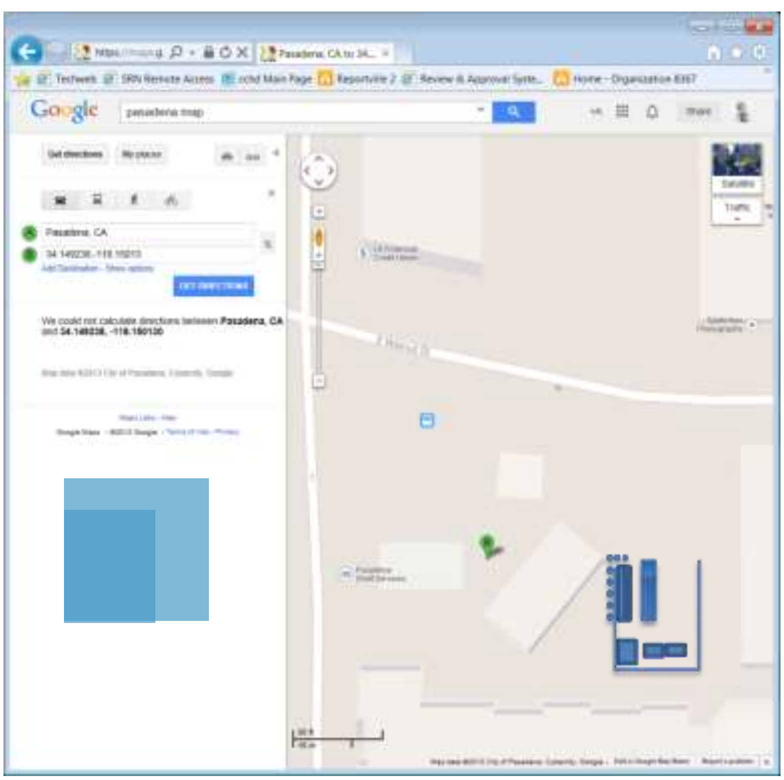
Pasadena #1



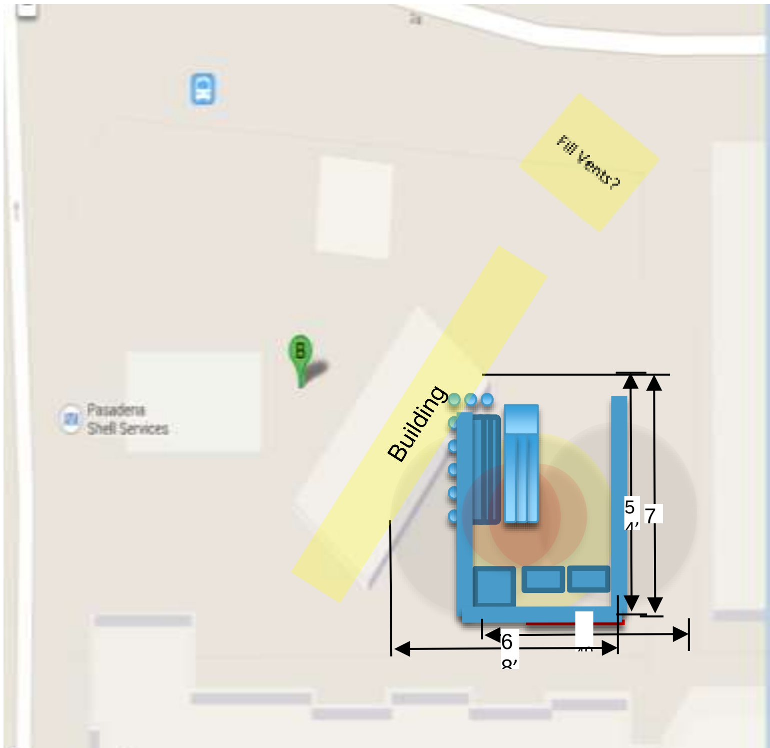
Pasadena #1



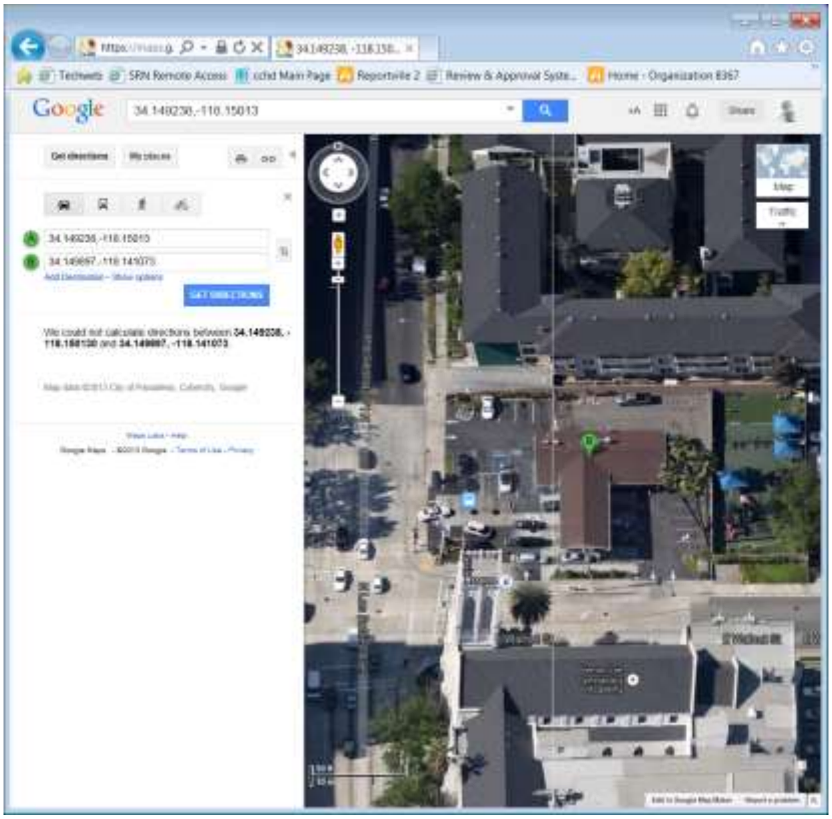
Pasadena #1



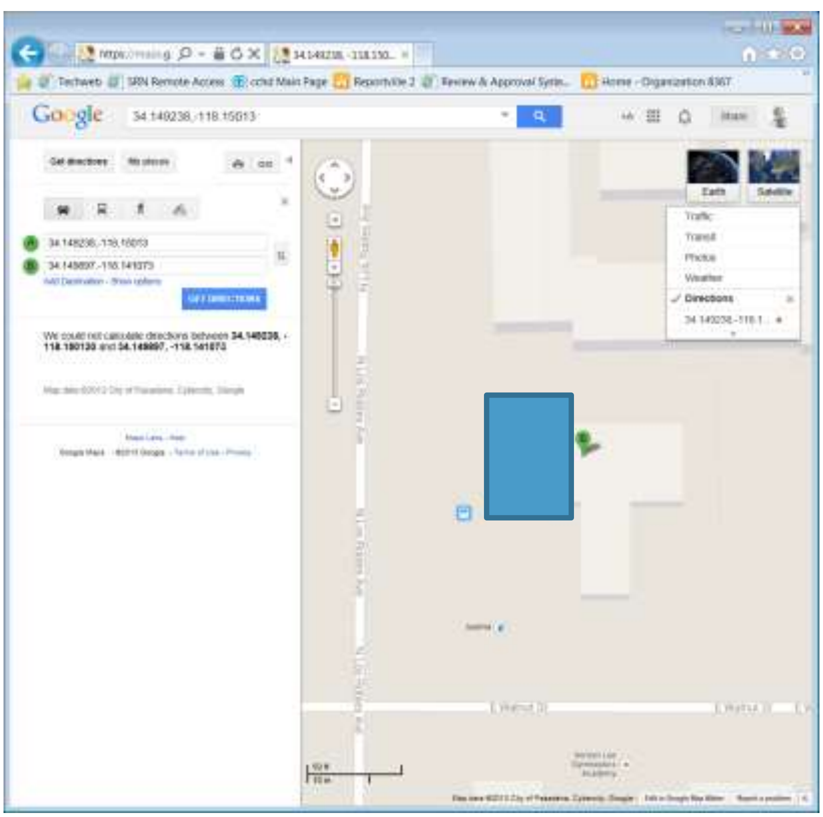
Pasadena #1



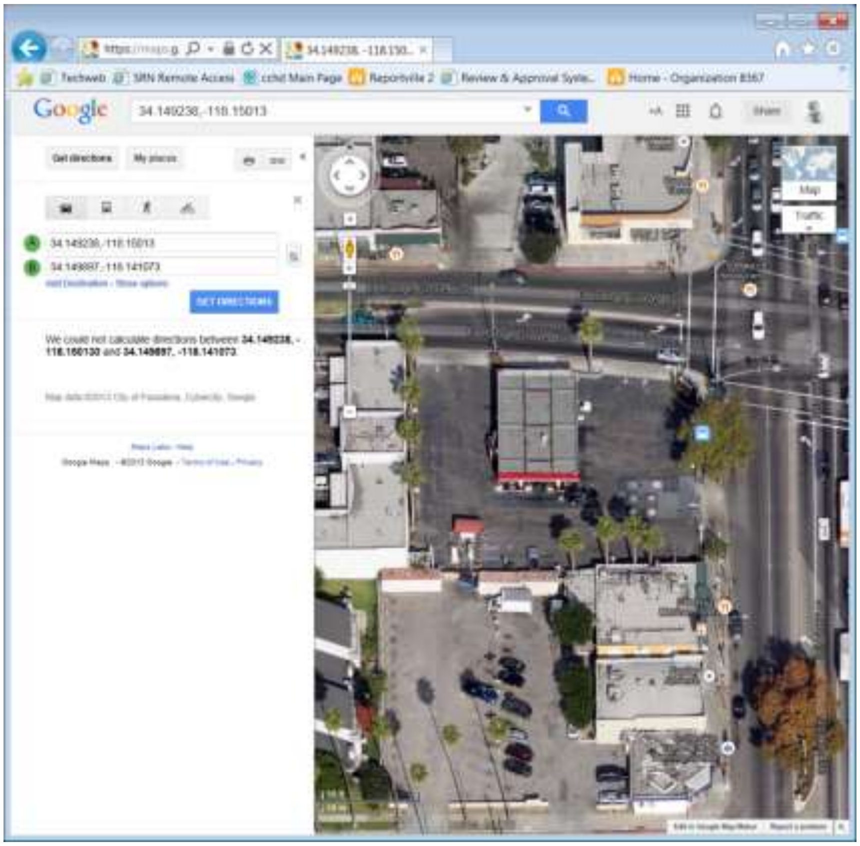
Pasadena #2



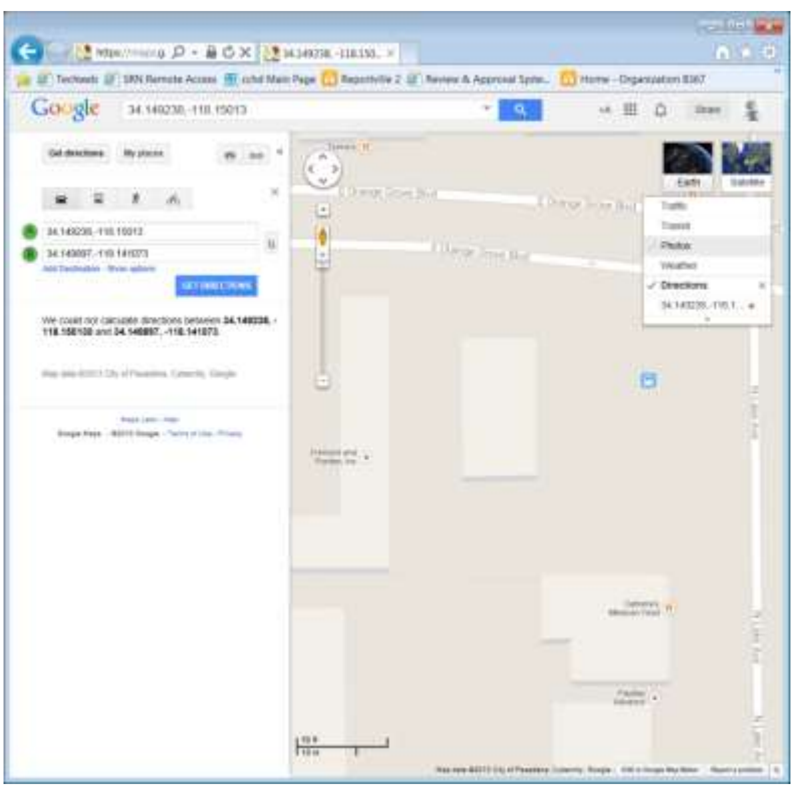
Pasadena #2



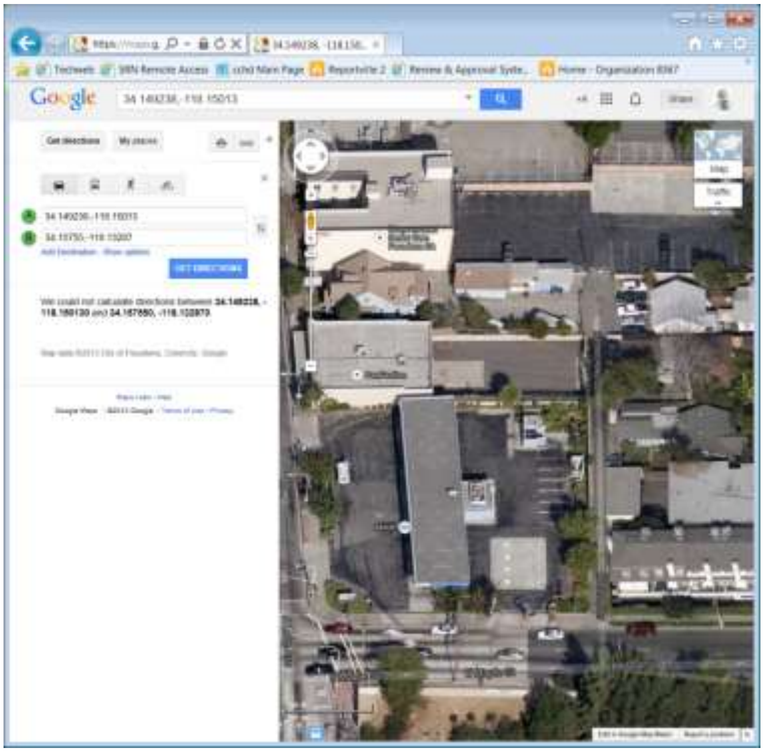
Pasadena #3



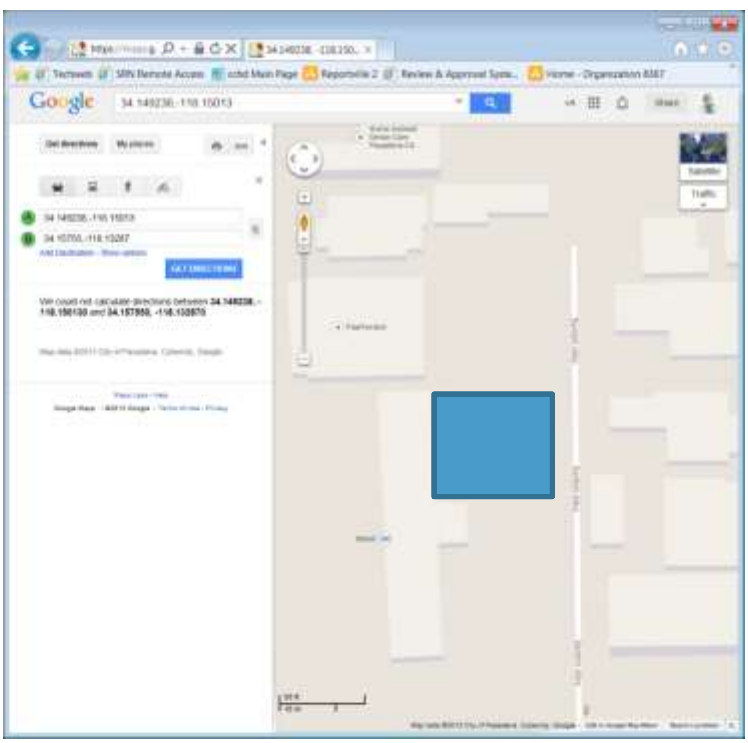
Pasadena #3



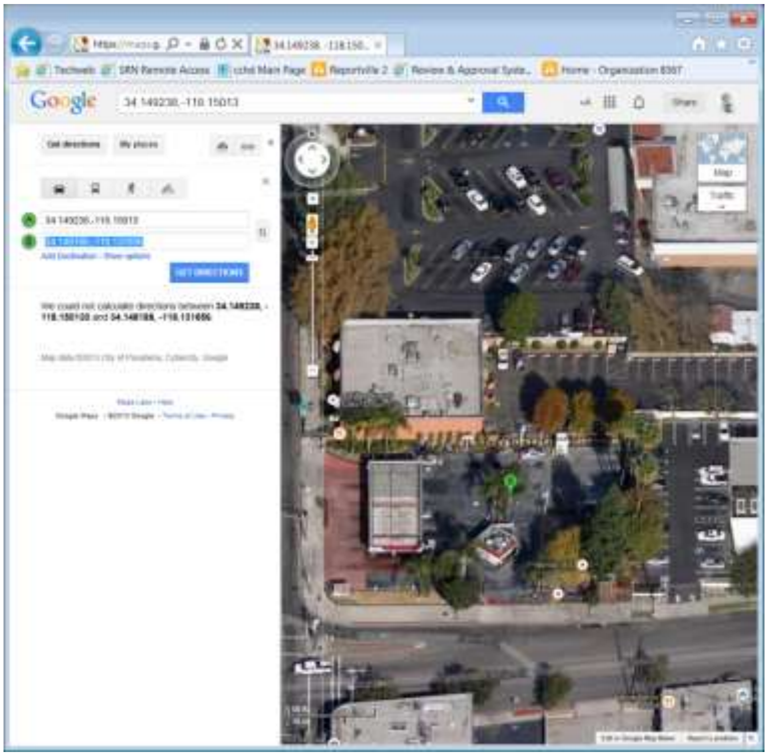
Pasadena #4



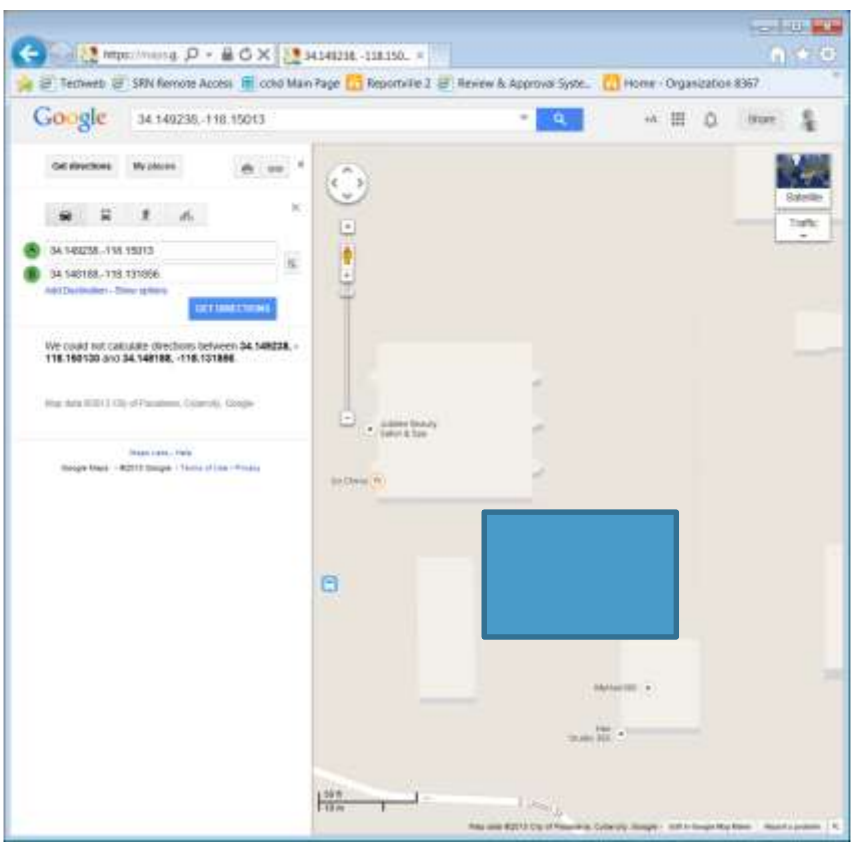
Pasadena #4



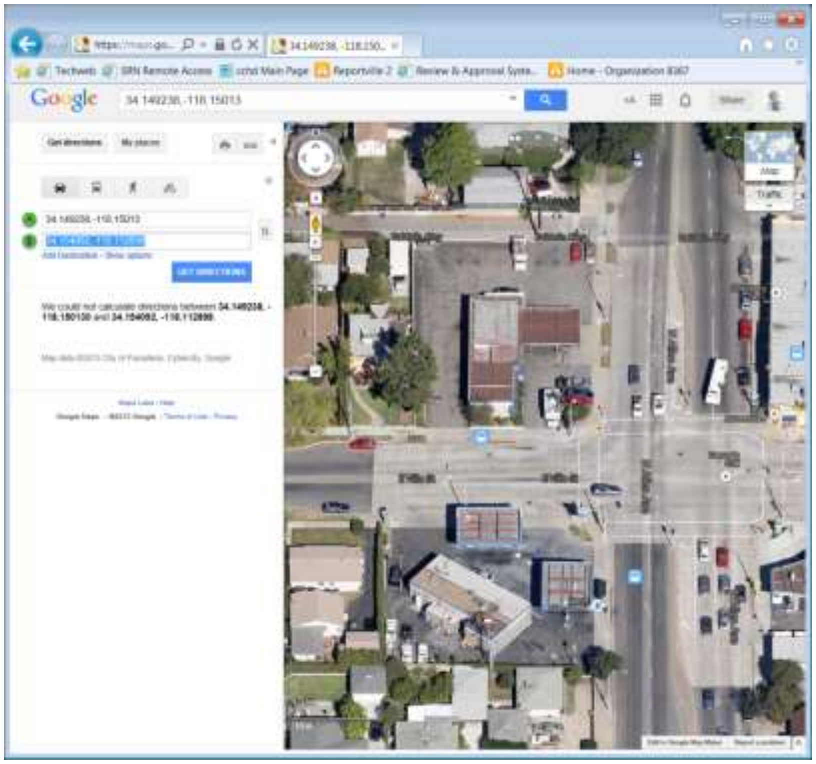
Pasadena #5



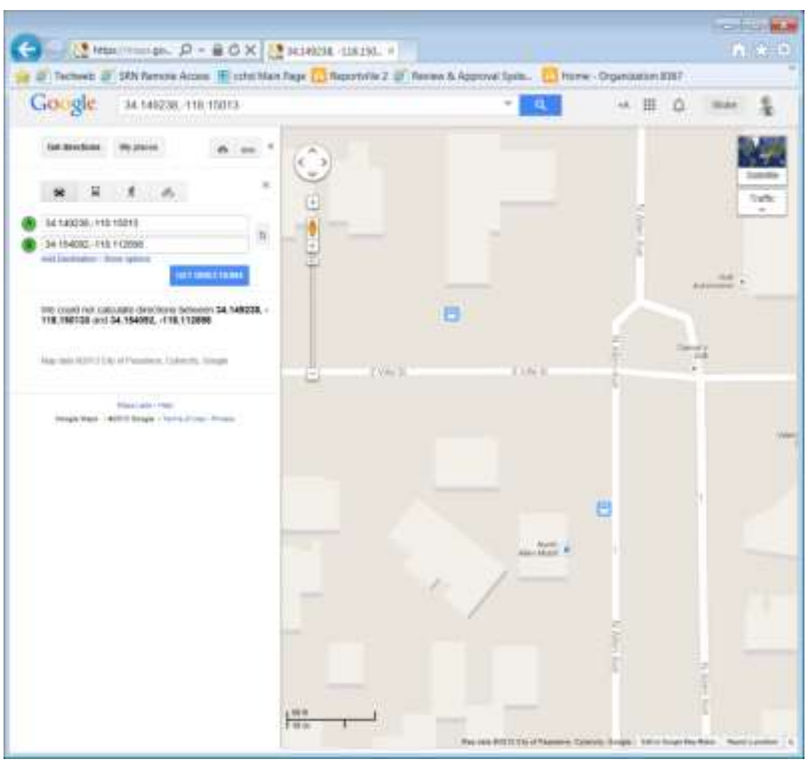
Pasadena #5



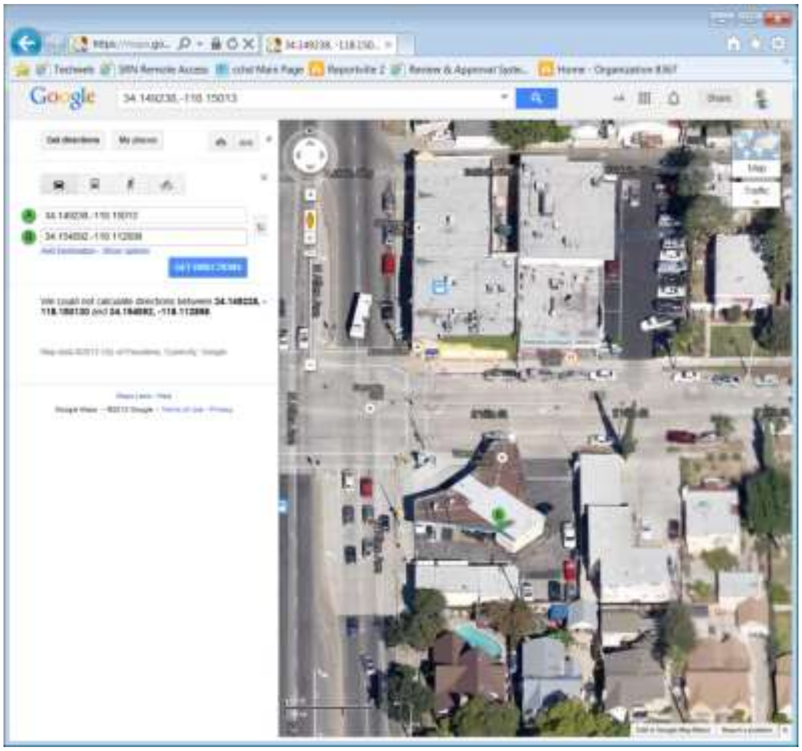
Pasadena #6



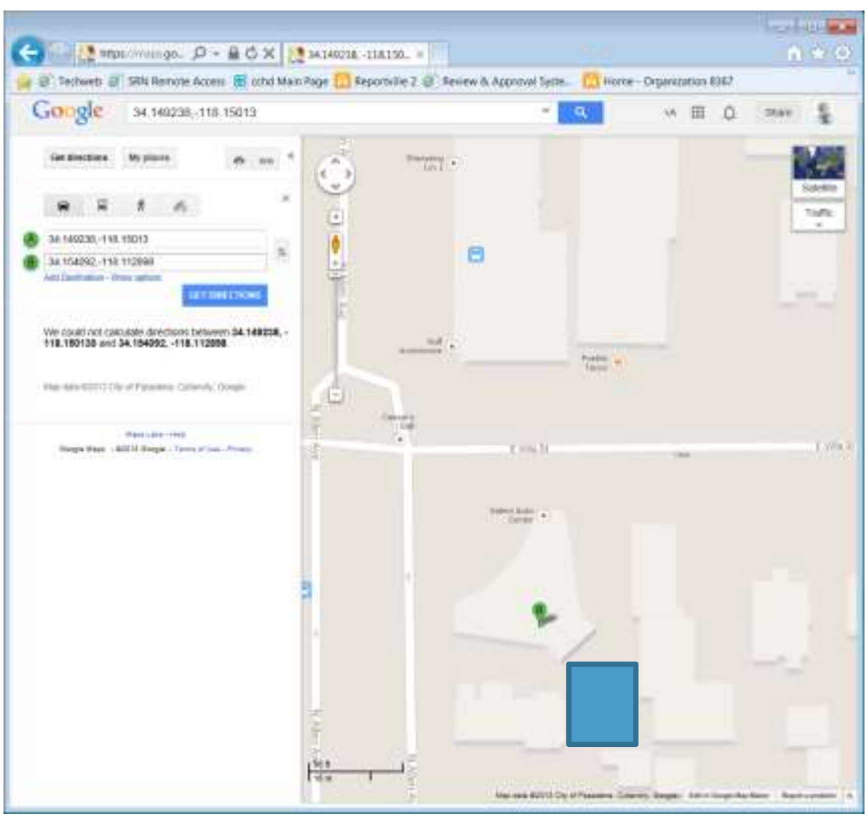
Pasadena #6



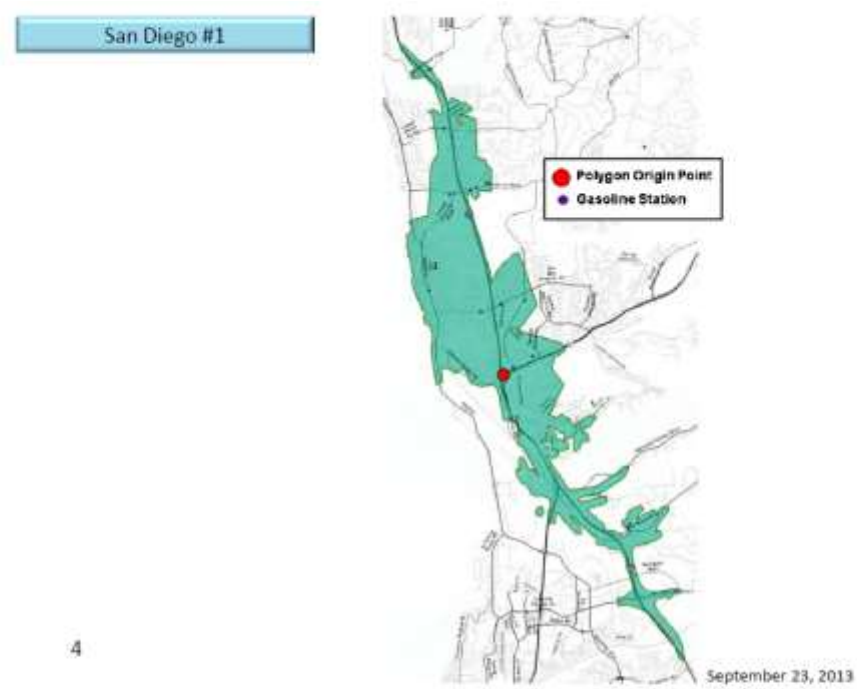
Pasadena #7



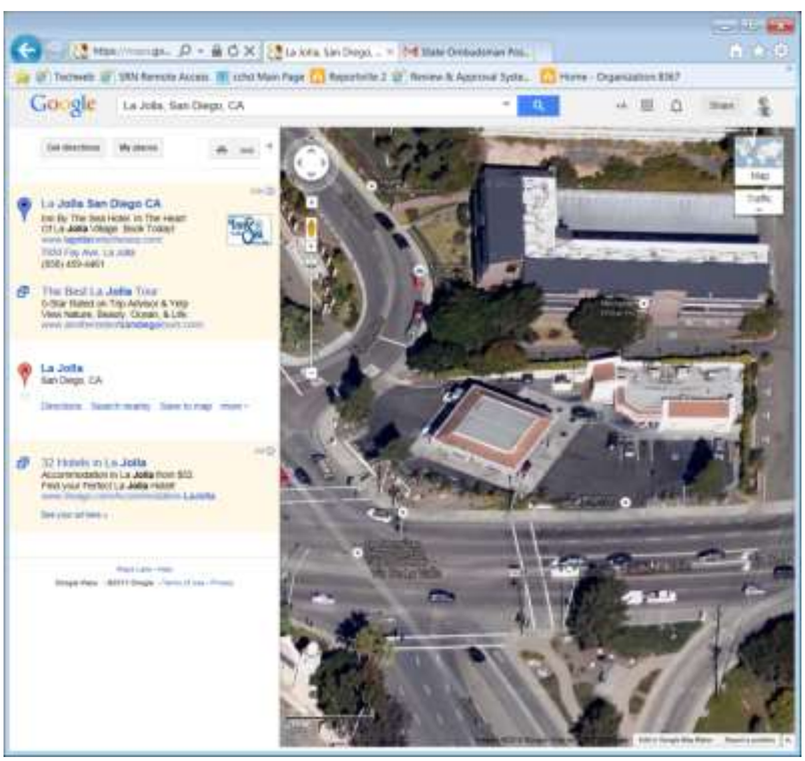
Pasadena #7



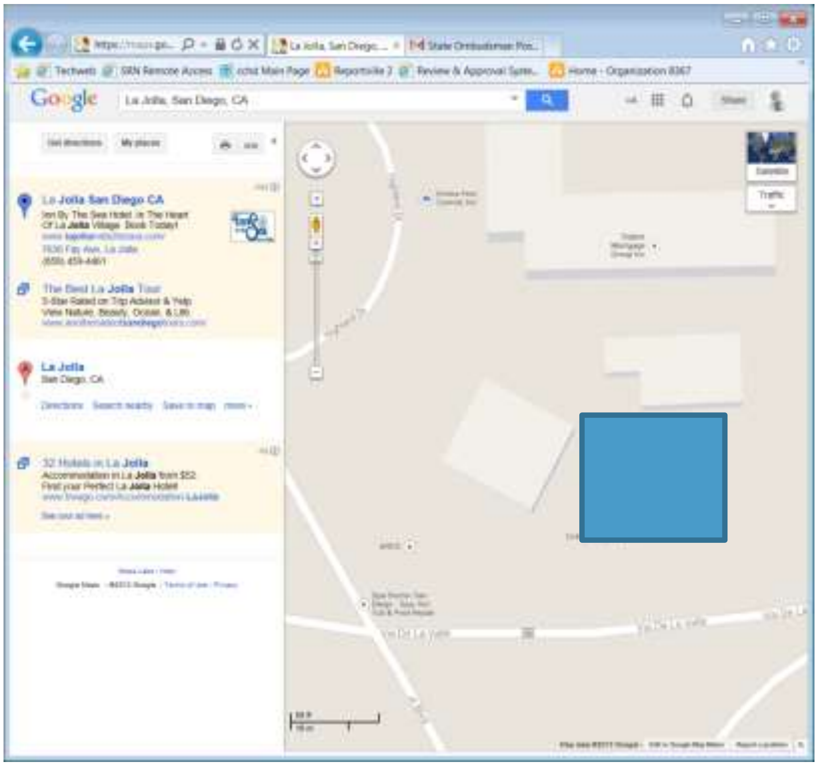
CEC Primary Area
San Diego #1 (13 stations)



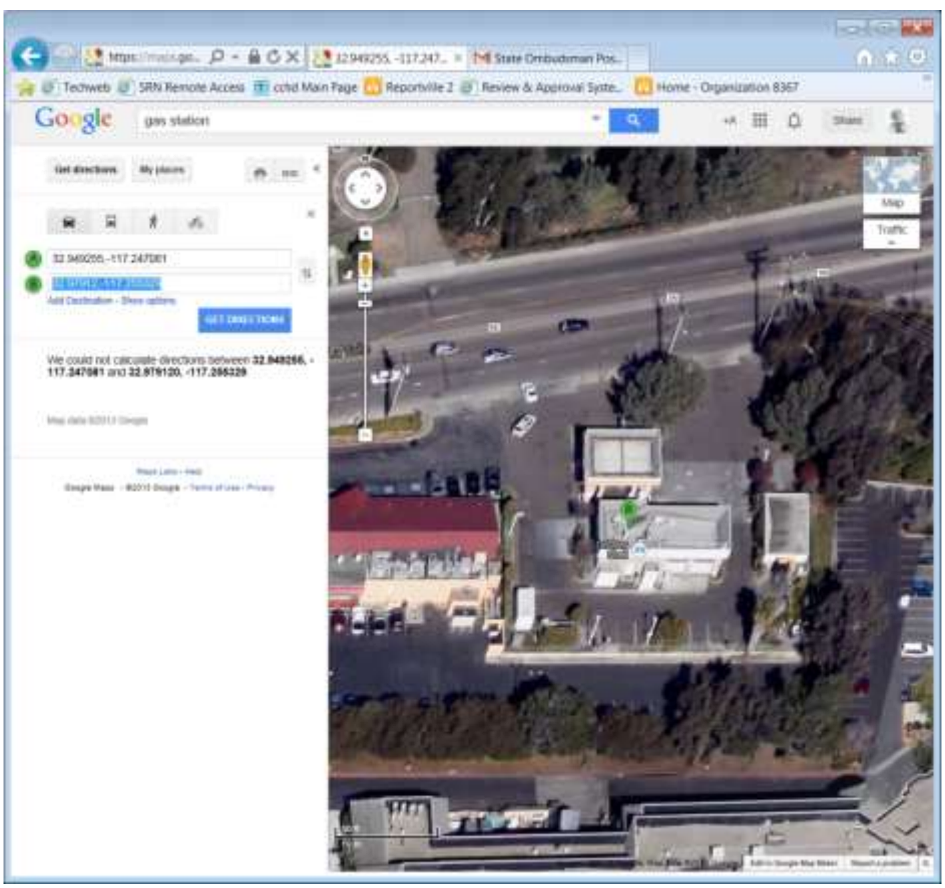
SD1 #1



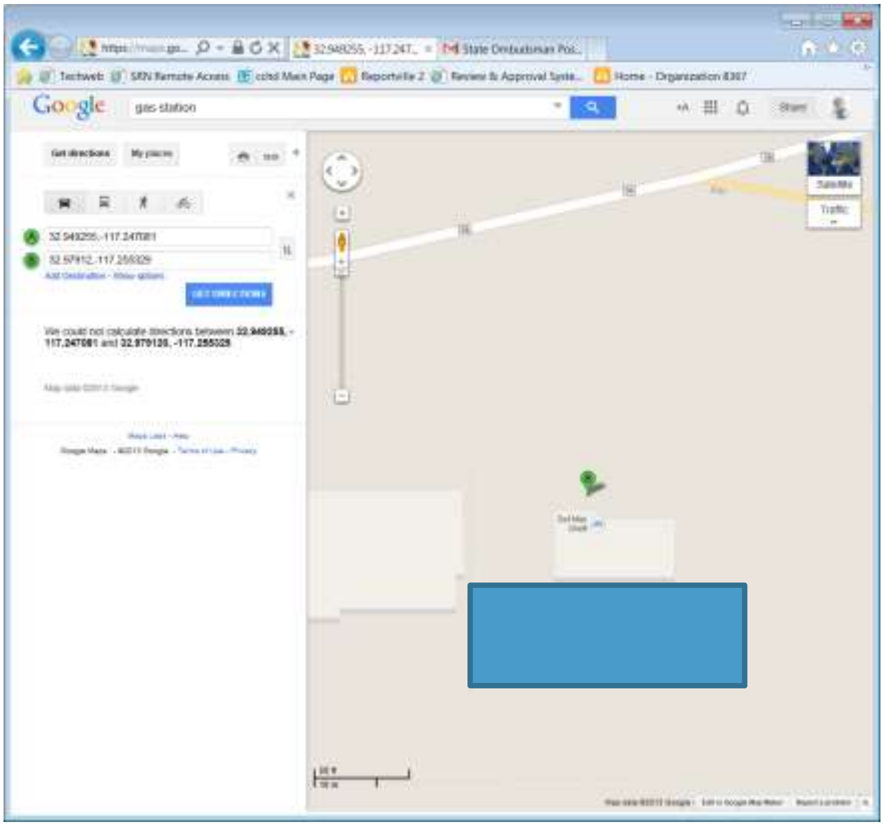
SD1 #1


Google
La Jolla, San Diego, CA
La Jolla San Diego CA
The Best La Jolla Tour
La Jolla
San Diego, CA
32 Hotels in La Jolla

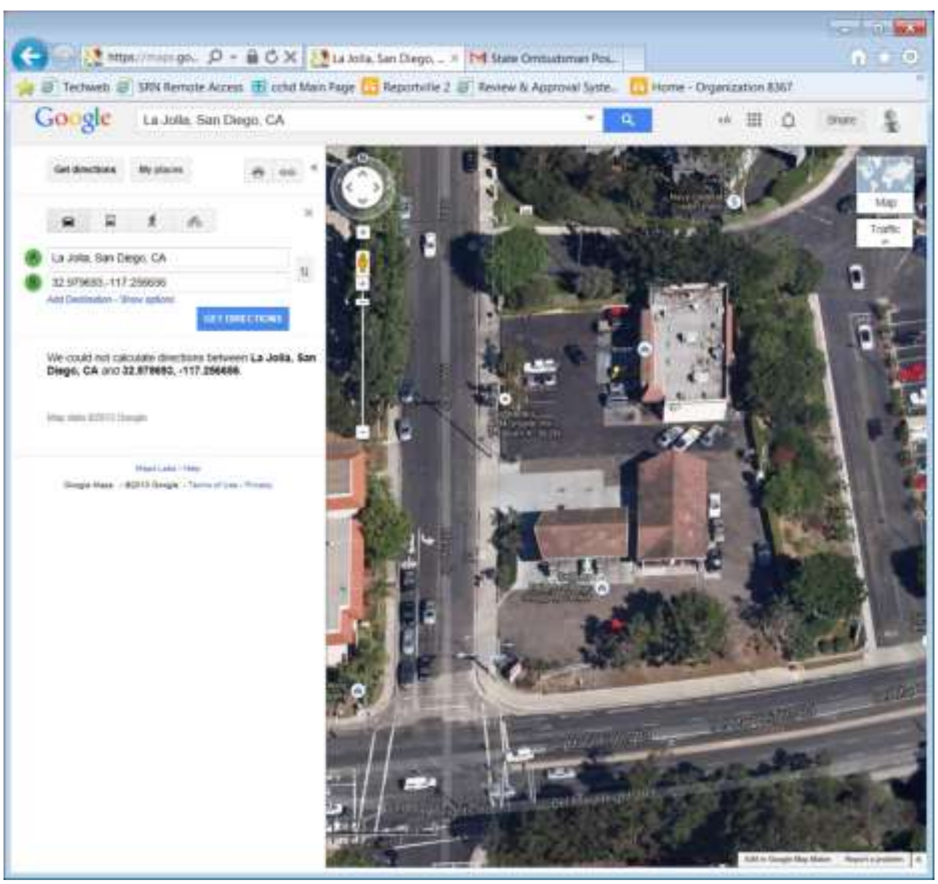
SD1 #2


Google
gas station
GET DIRECTIONS

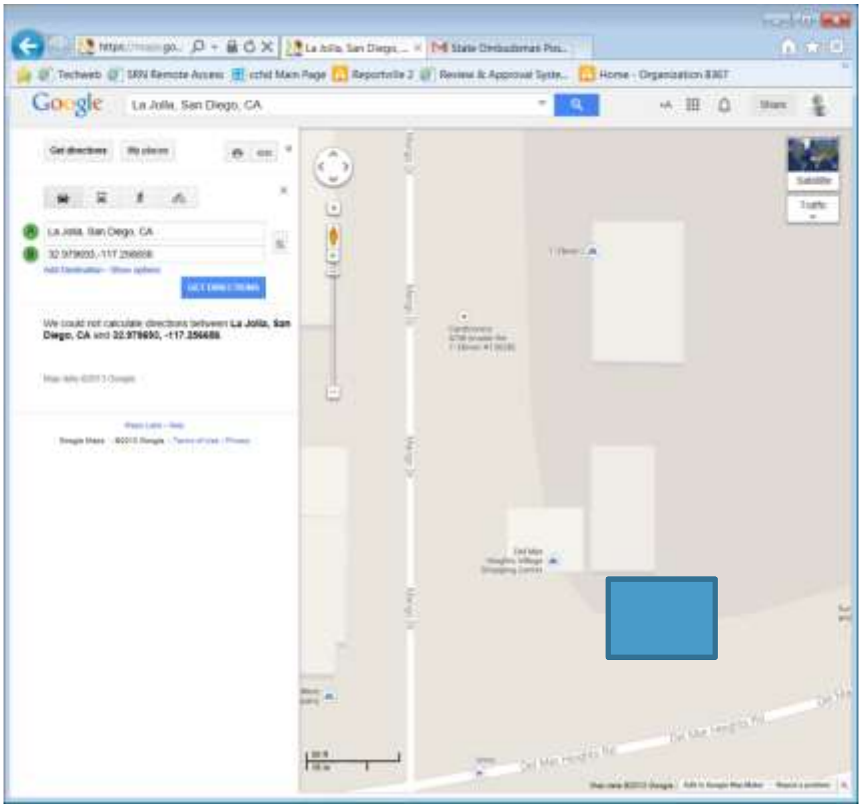
SD1 #2


Techweb
SRN Remote Access
cchd Main Page
State Ombudsman Pos...
Home - Organization 8367
Google
gas station
Get directions
My places
Satellite
Traffic

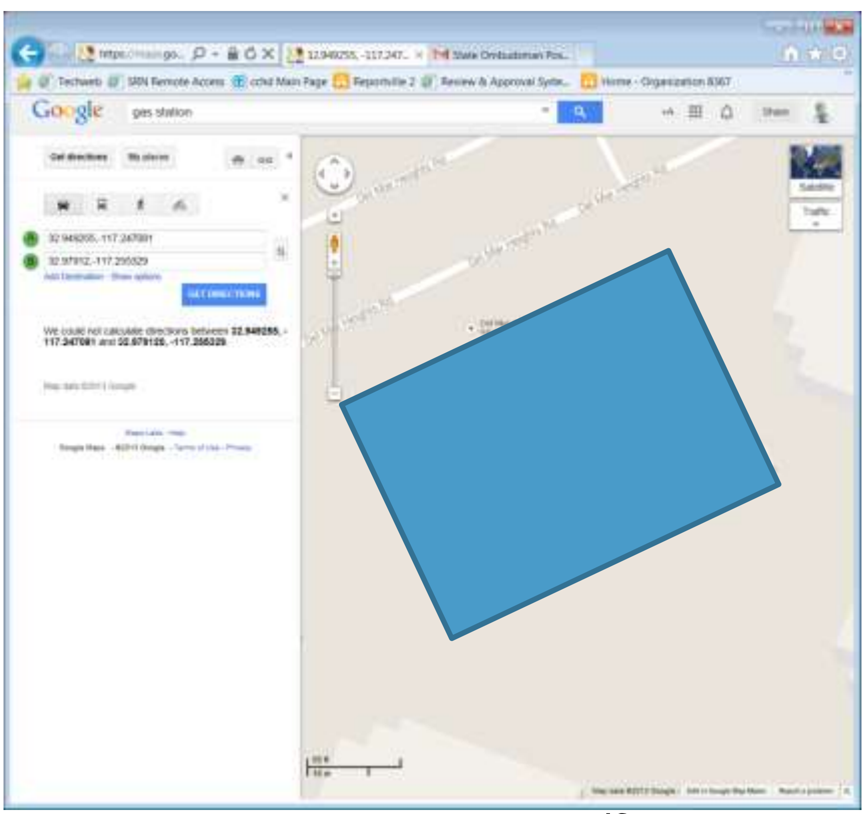
SD1 #3


La Jolla, San Diego, ...
State Ombudsman Pos...
Techweb
SRN Remote Access
cchd Main Page
Reportville 2
Review & Approval Syste...
Home - Organization 8367
Google
La Jolla, San Diego, CA
Get directions
My places
La Jolla, San Diego, CA
GET DIRECTIONS
We could not calculate directions between La Jolla, San Diego, CA and
Map
Traffic

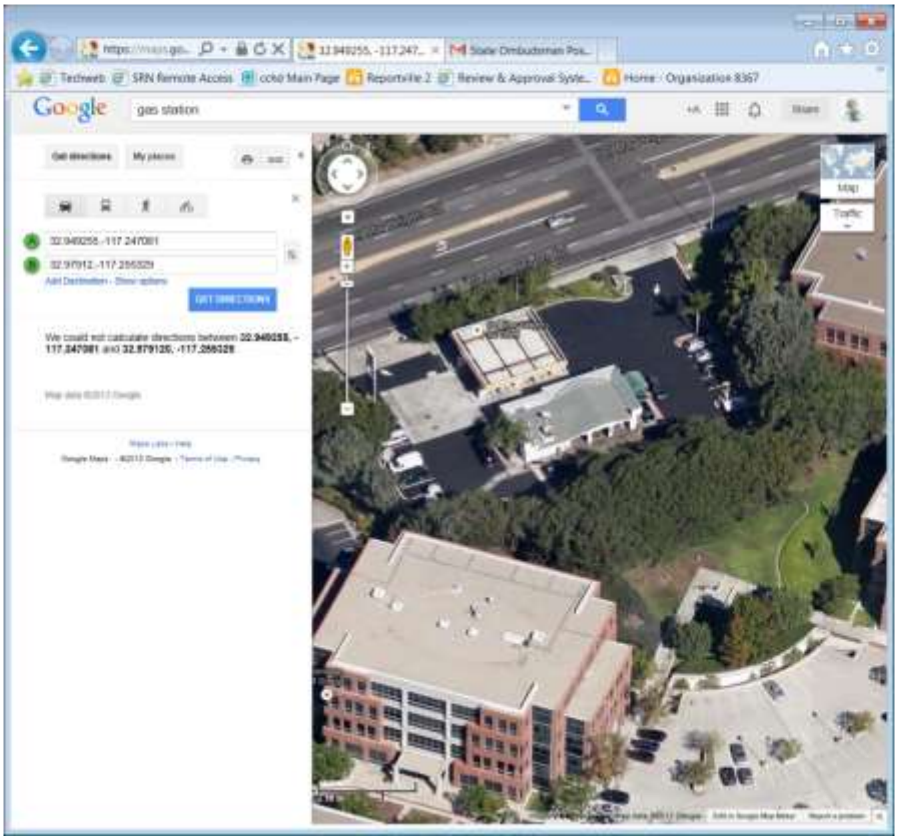
SD1 #3


Google
La Jolla, San Diego, CA
Techweb
SRN Remote Access
cchd Main Page
Reportville 2
Home - Organization 8367

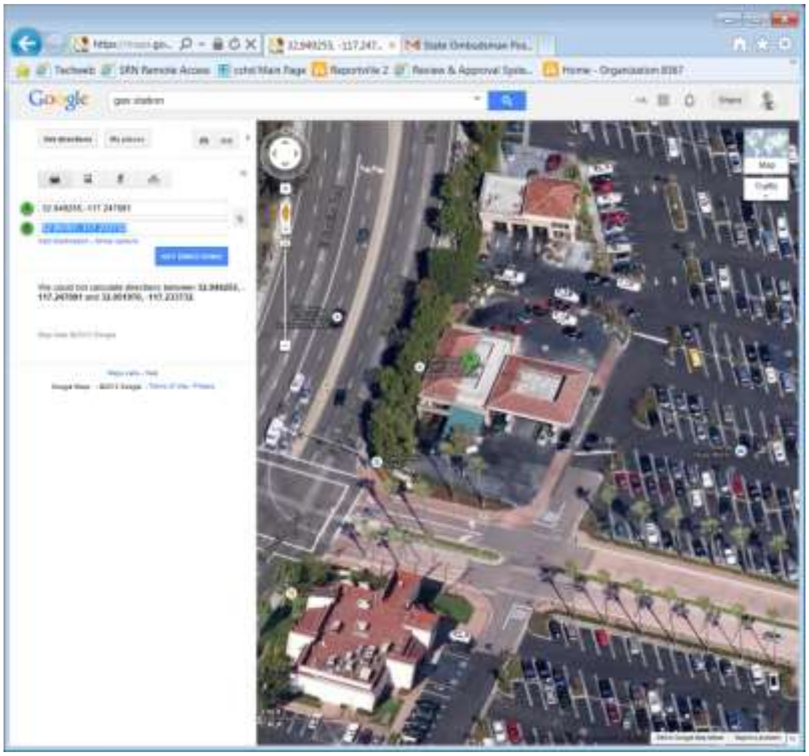
SD1 #4


Google
gas station
Techweb
SRN Remote Access
cchd Main Page
Reportville 2
Home - Organization 8367

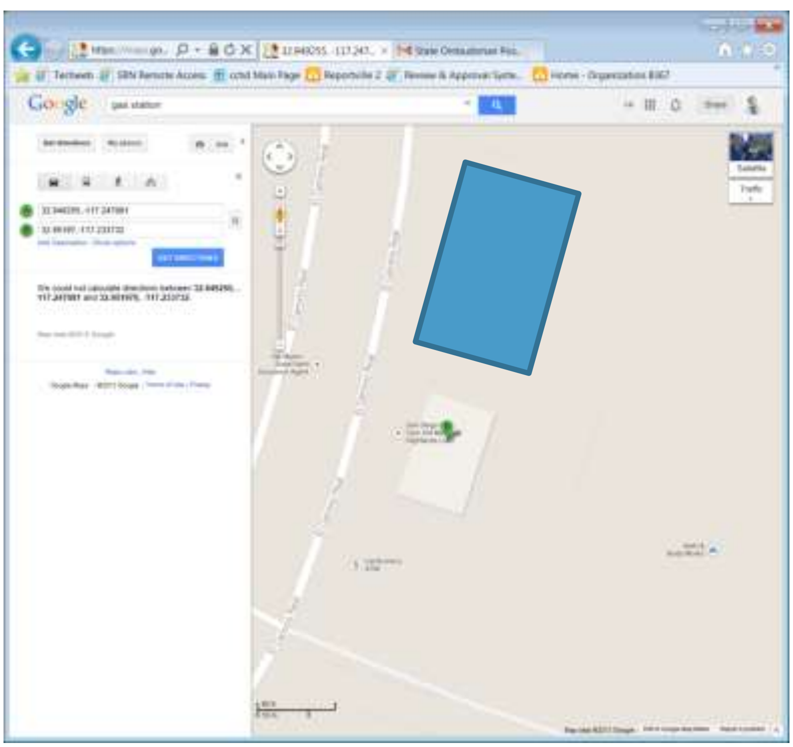
SD1 #4



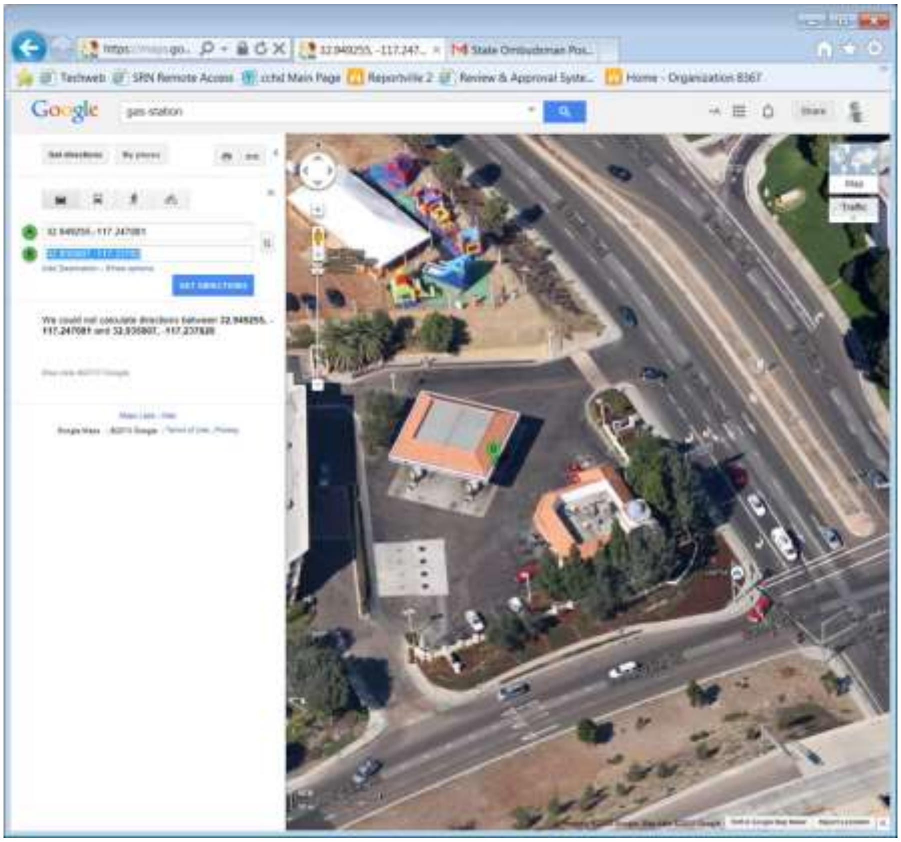
SD1 #5



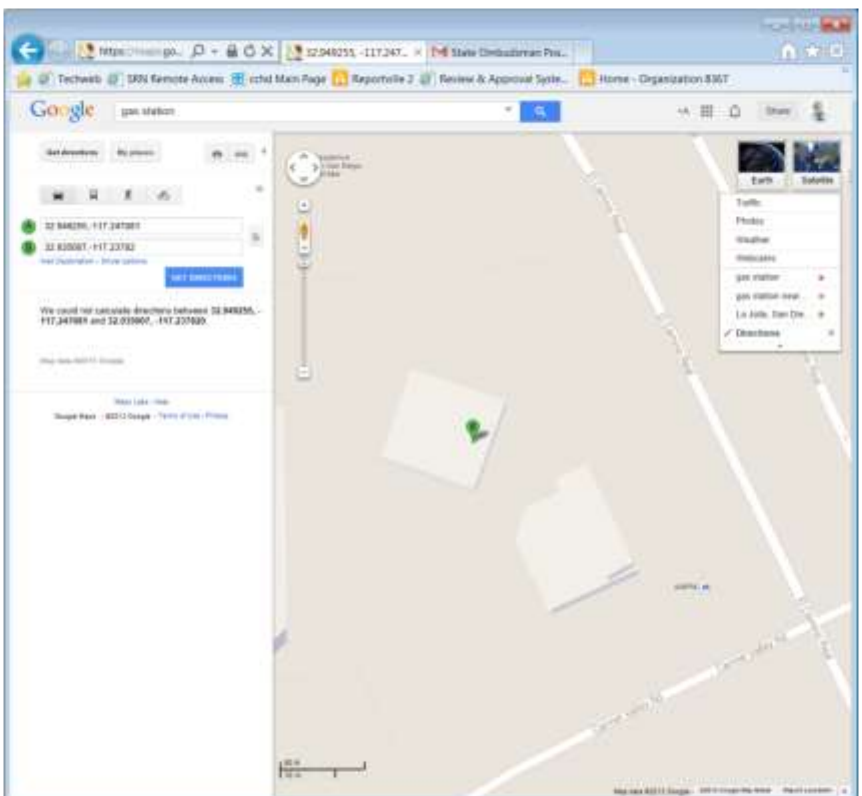
SD1 #5



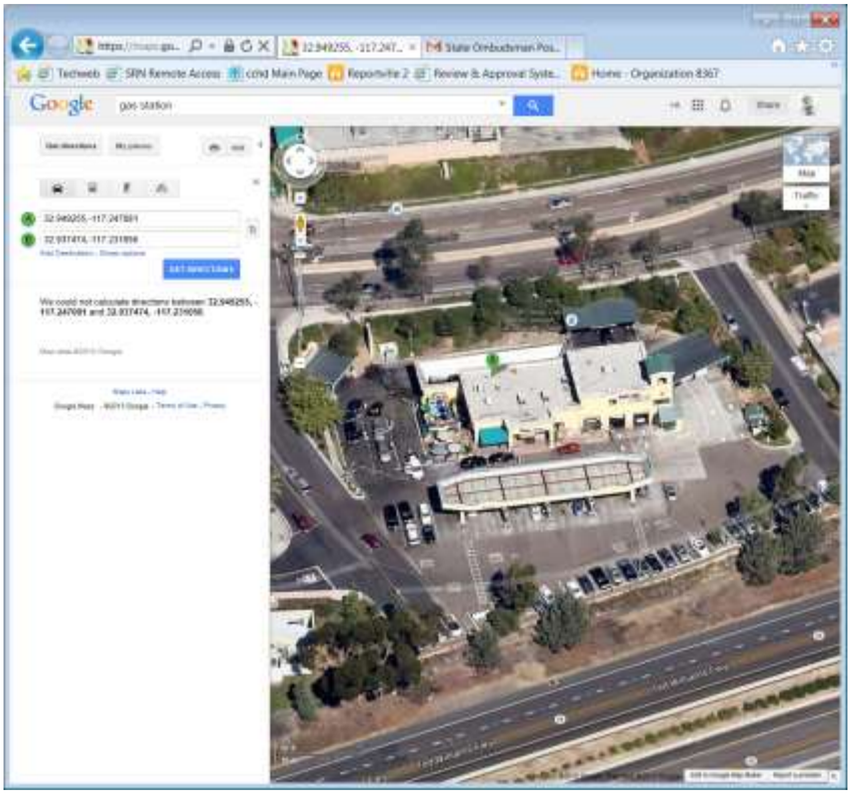
SD1 #6



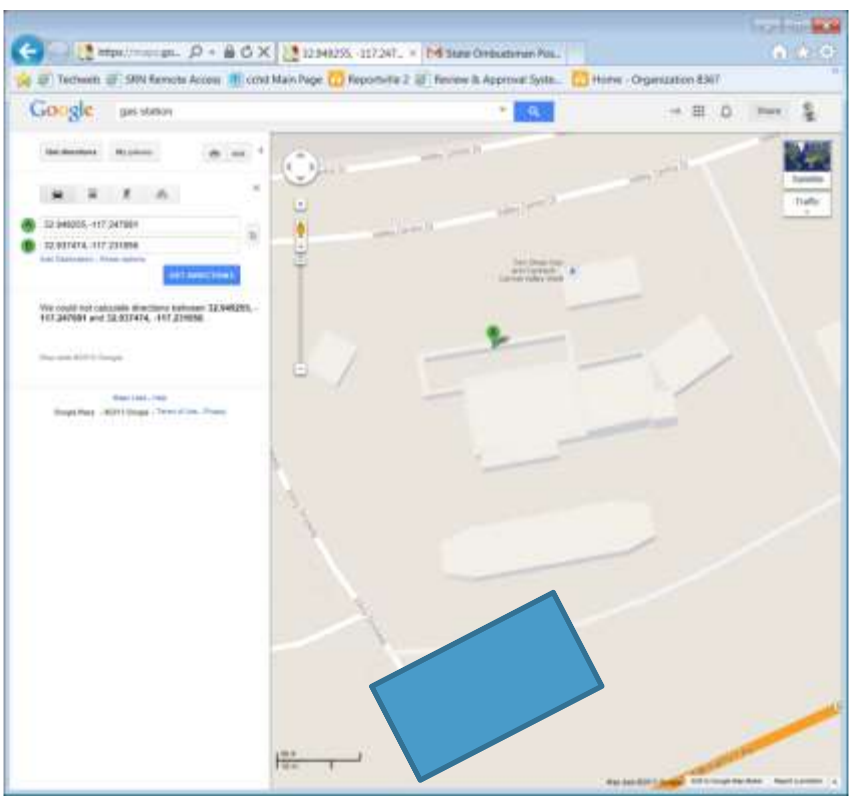
SD1 #6



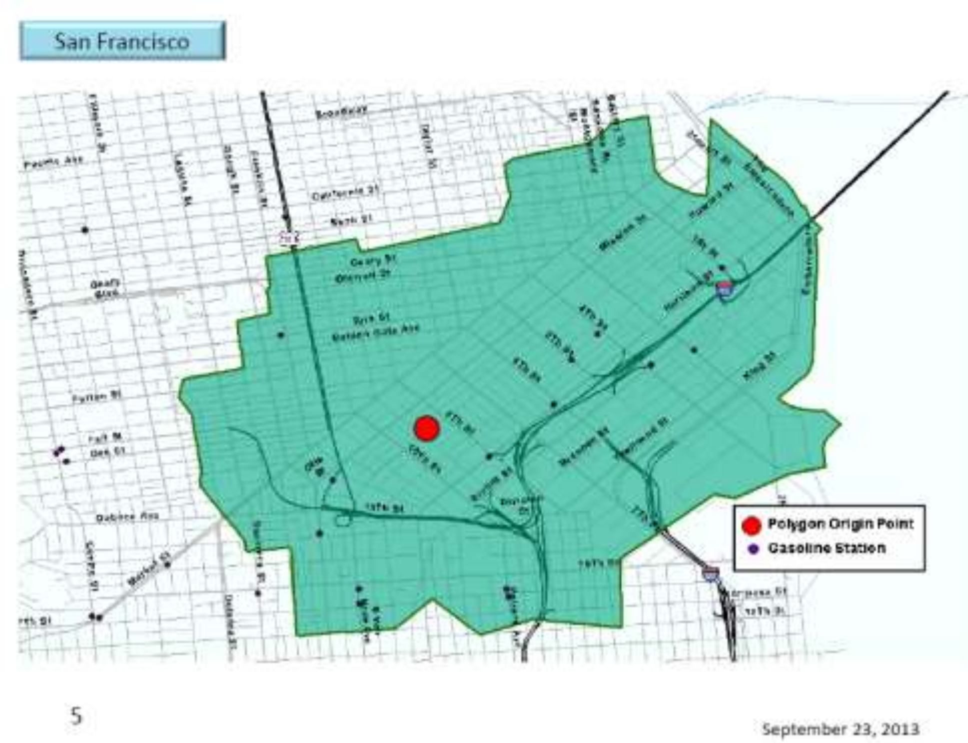
SD1 #7


Google
gas station
Techweb
SRN Remote Access
Home - Organization 8367

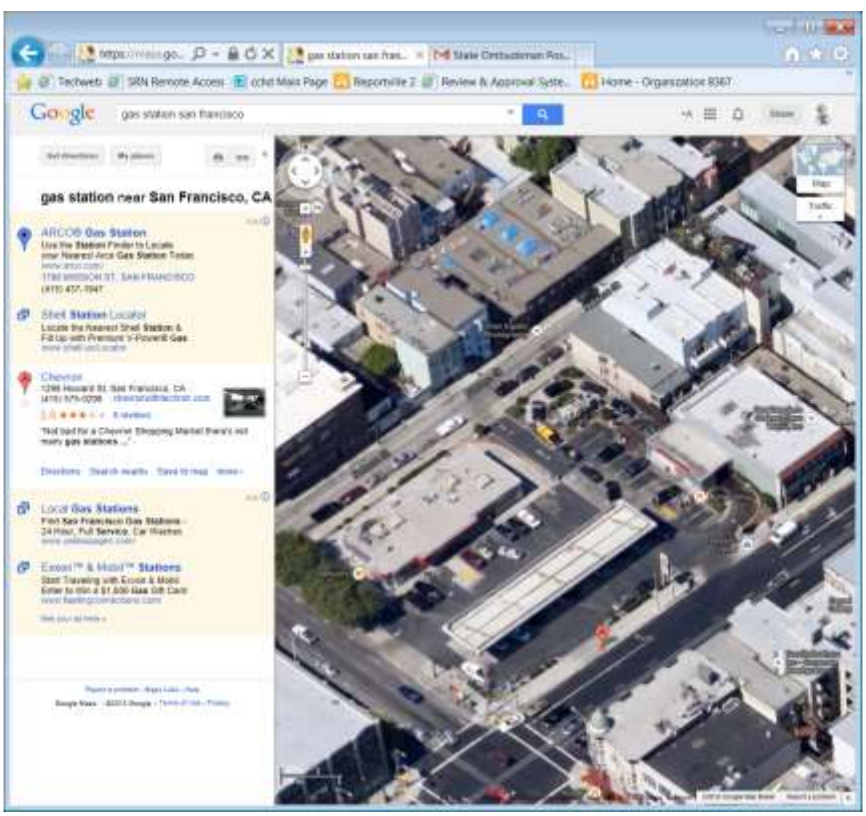
SD1 #7


Google
gas station
Techweb
SRN Remote Access
Home - Organization 8367

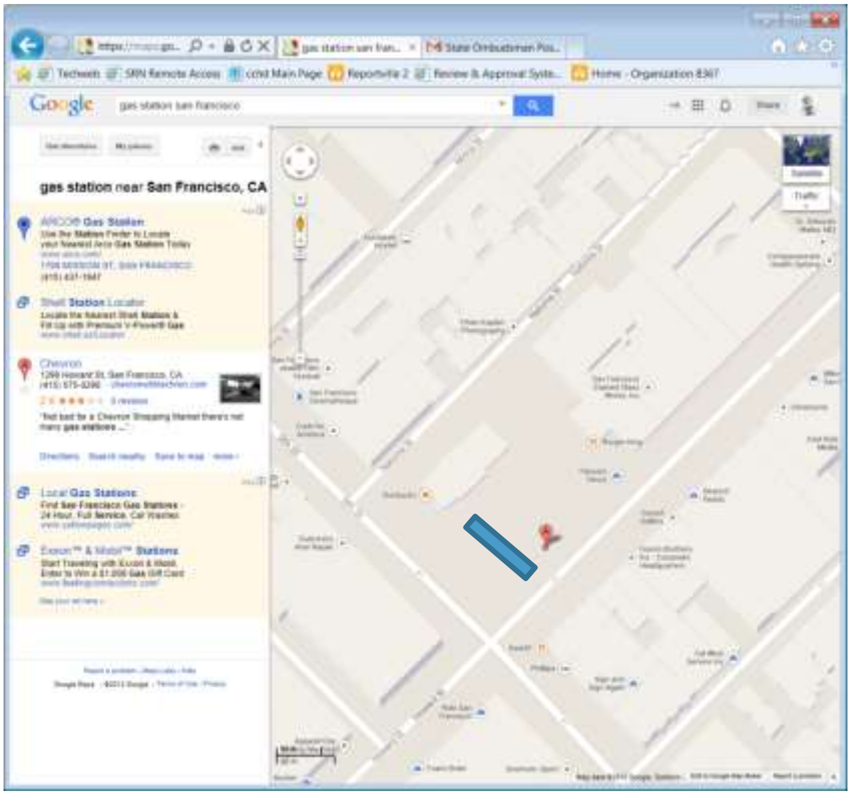
CEC Primary Area
San Francisco (14 stations)



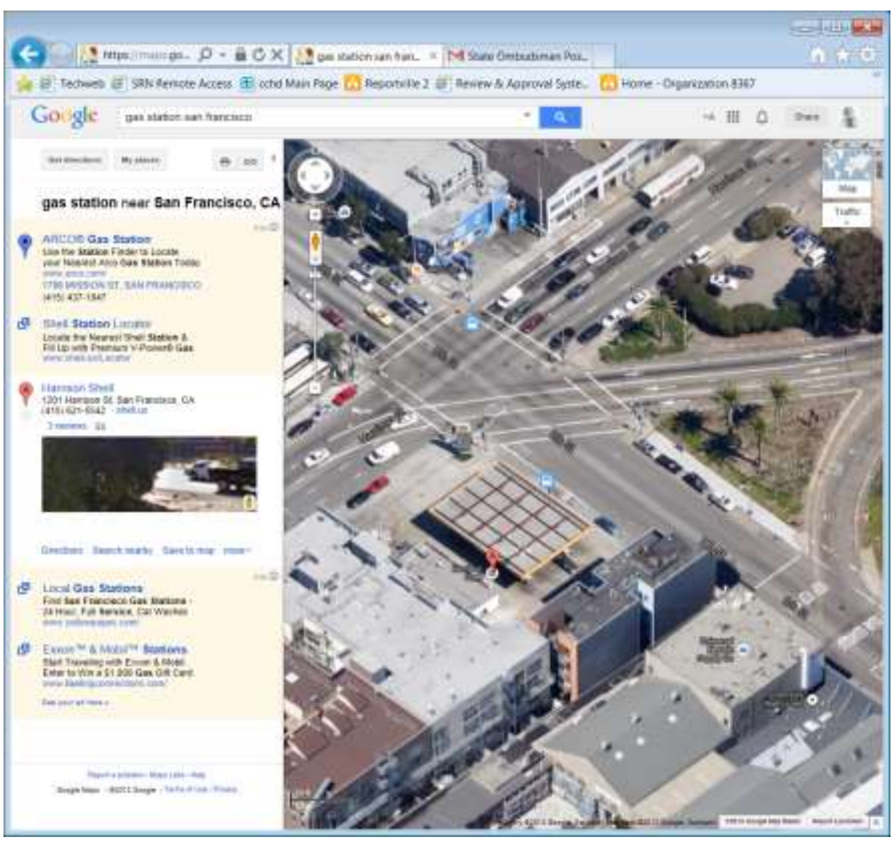
SF1 #1



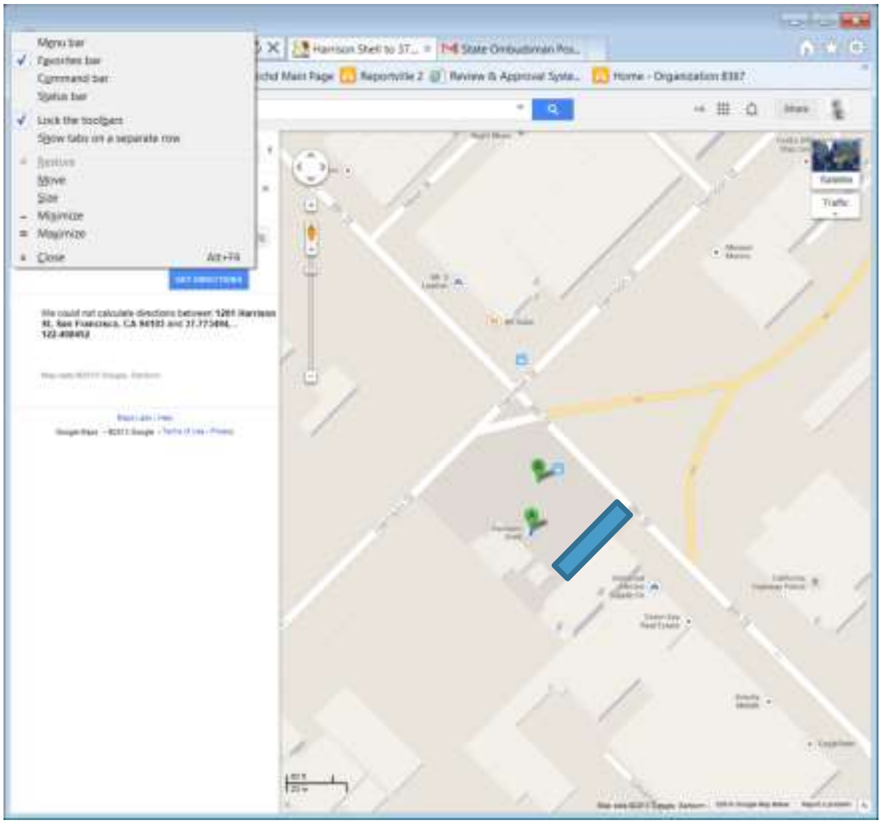
SF1 #1


Techweb
SRN Remote Access
cchd Main Page
Home - Organization 8367
Google
gas station san francisco
gas station near San Francisco, CA
ARCO® Gas Station
Shell Station Locator
Chevron
Local Gas Stations
Exxon™ & Mobil™ Stations

SF1 #2

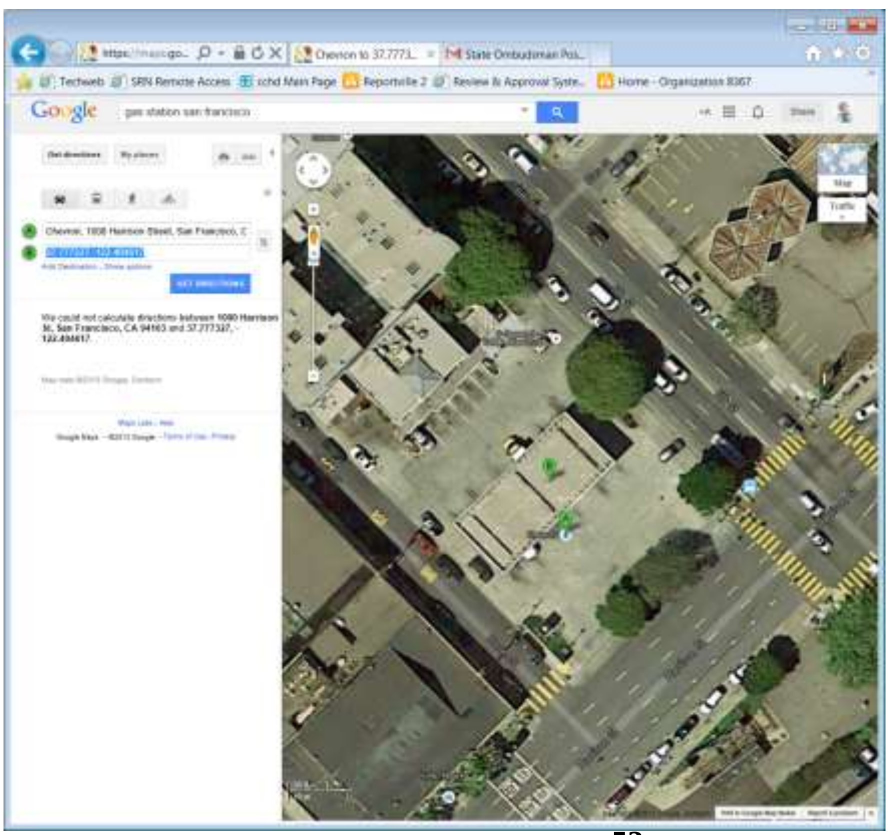

Techweb
SRN Remote Access
cchd Main Page
Reportville 2
Review & Approval Syste...
Home - Organization 8367
Google
gas station san francisco
gas station near San Francisco, CA
ARCO® Gas Station
Shell Station Locator
Harrison Shell
1201 Harrison St, San Francisco, CA
Local Gas Stations
Exxon™ & Mobil™ Stations

SF1 #2



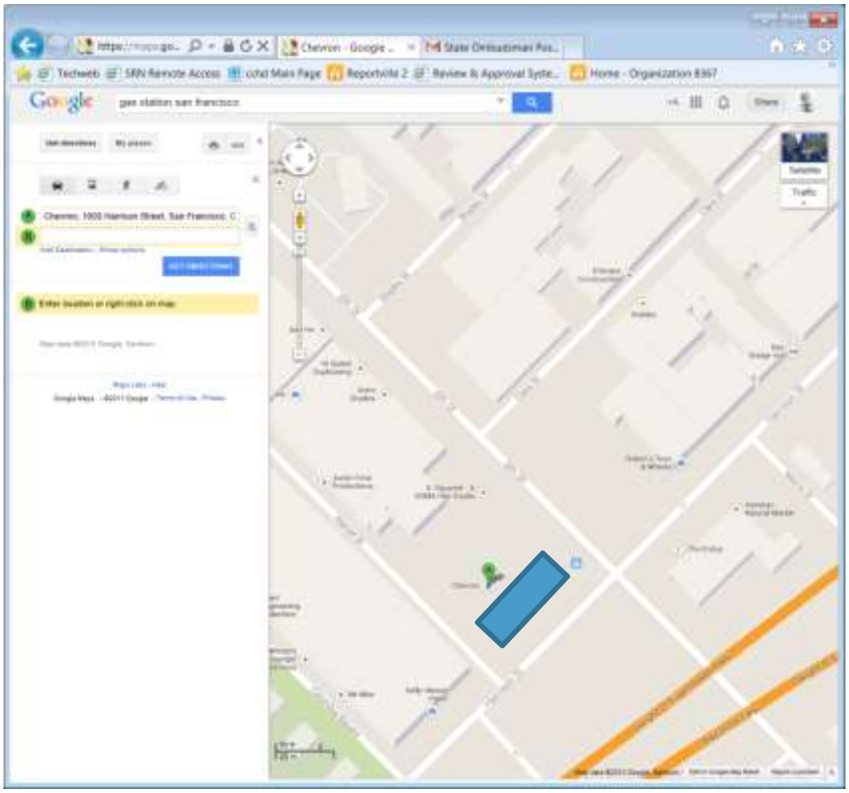
Menu bar
Favorites bar
Command bar
Status bar
Lock the toolbars
Show tabs on a separate row
Restore
Move
Size
Minimize
Maximize
Close
Alt+F4

SF1 #3

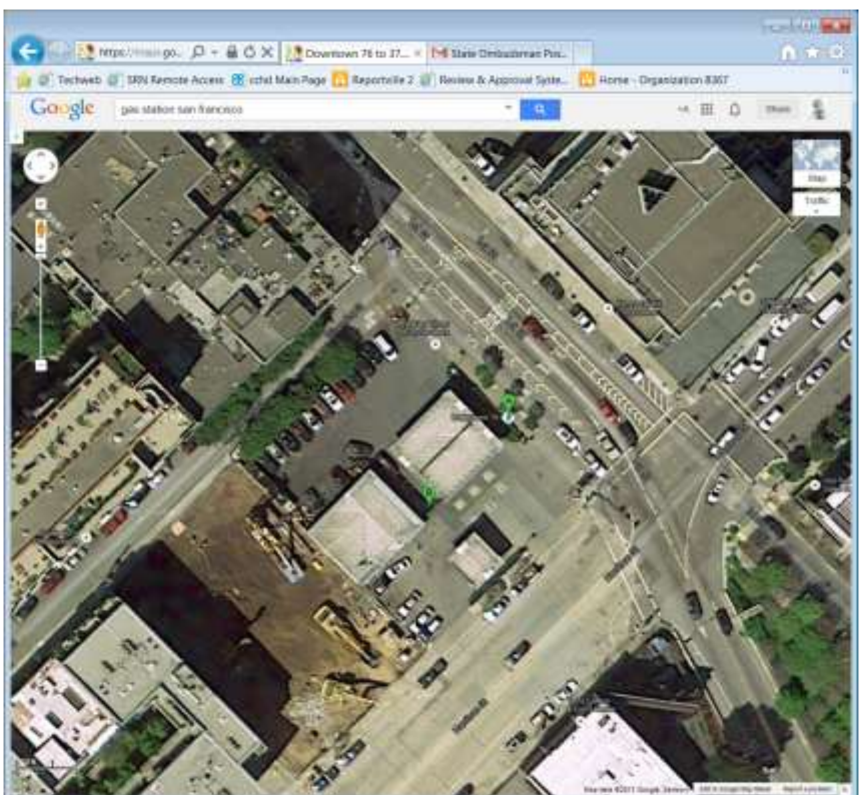


Google
gas station san francisco

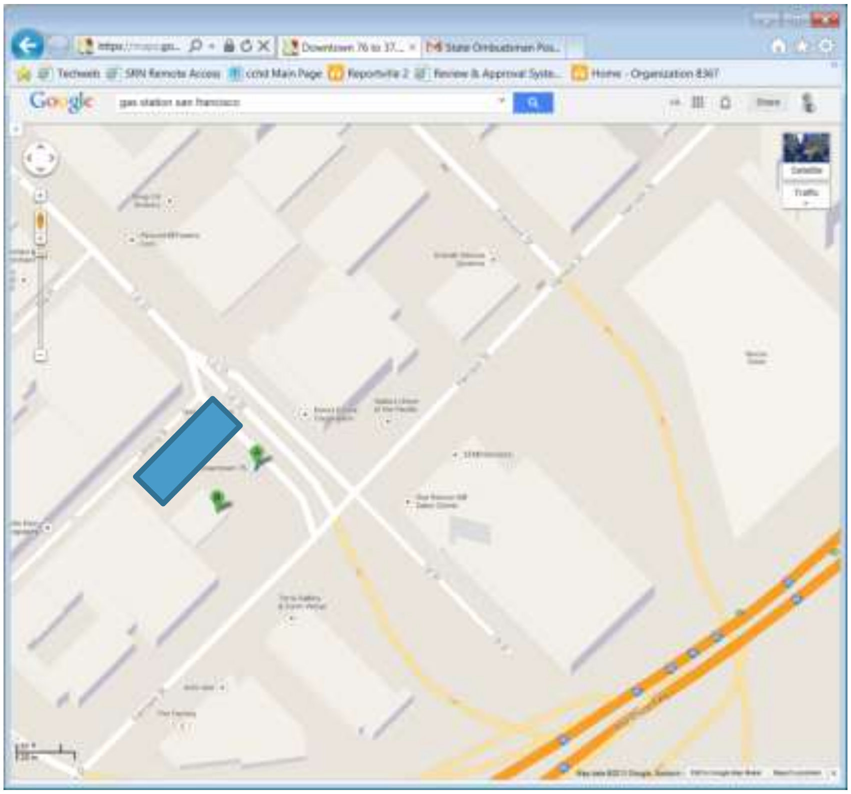
SF1 #3


Google
gas station san francisco
Techweb
SRN Remote Access
cchd Main Page
Reportville 2
Home - Organization 8367

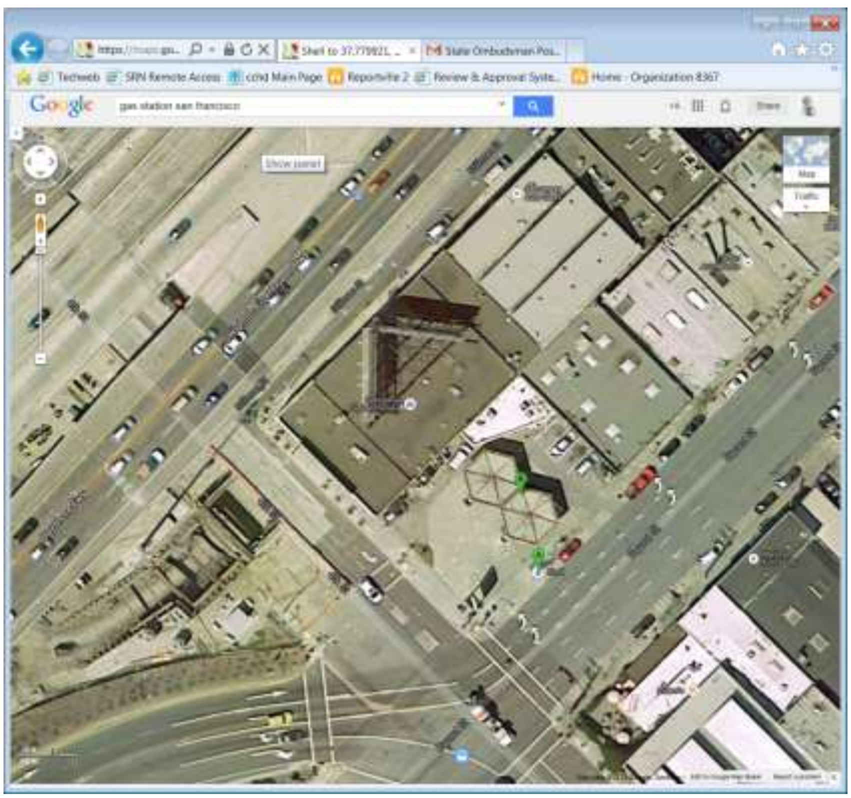
SF1 #4


Google
gas station san francisco
Techweb
SRN Remote Access
cchd Main Page
Reportville 2
Home - Organization 8367

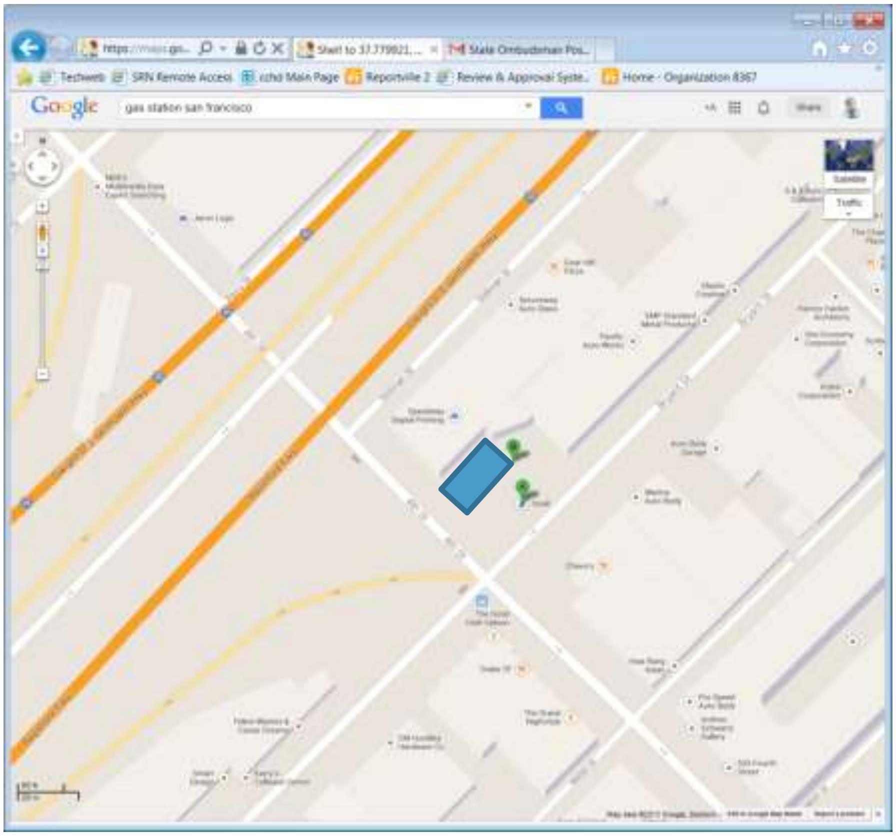
SF1 #4



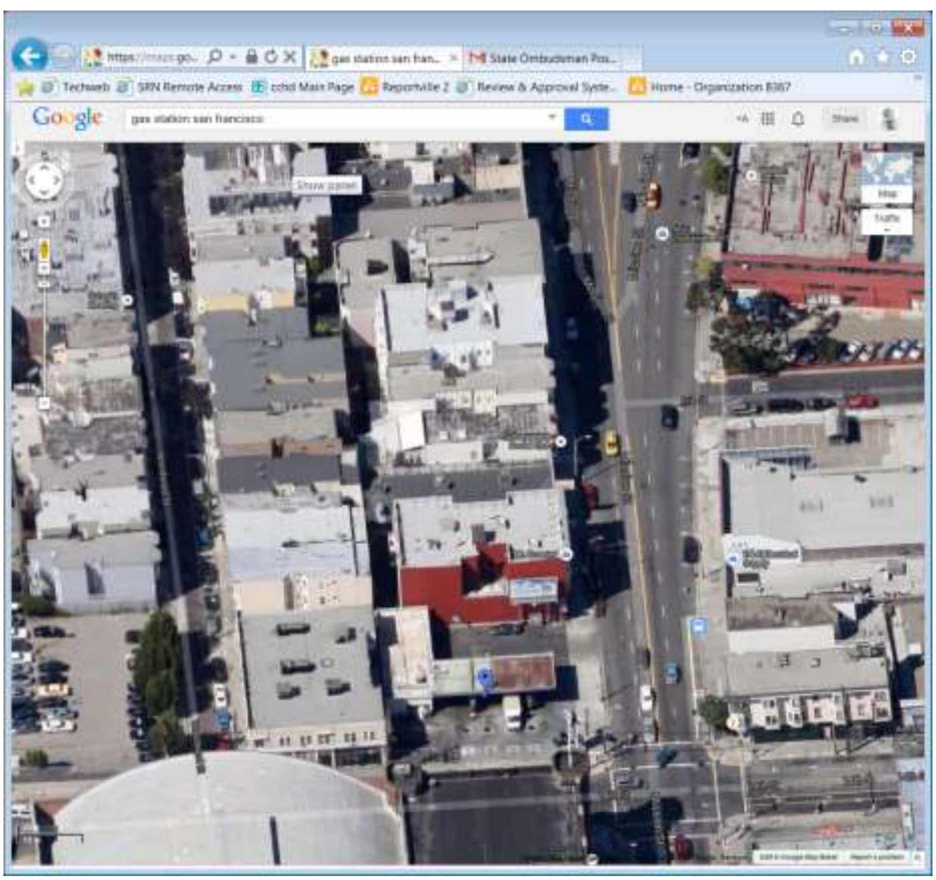
SF1 #5



SF1 #5



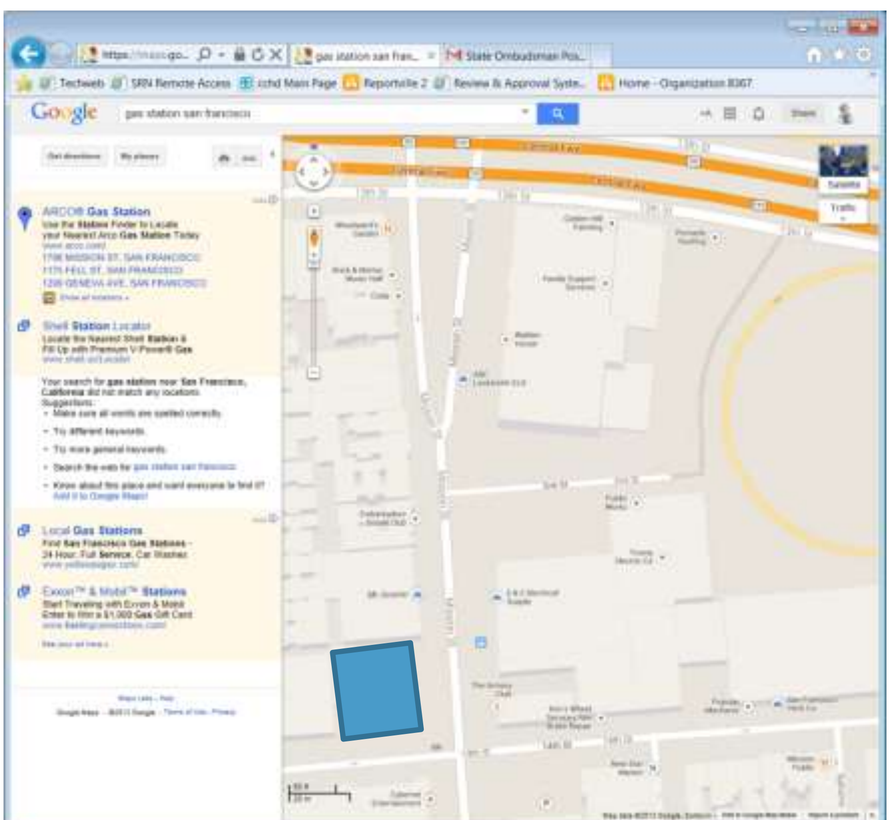
#SF1 6



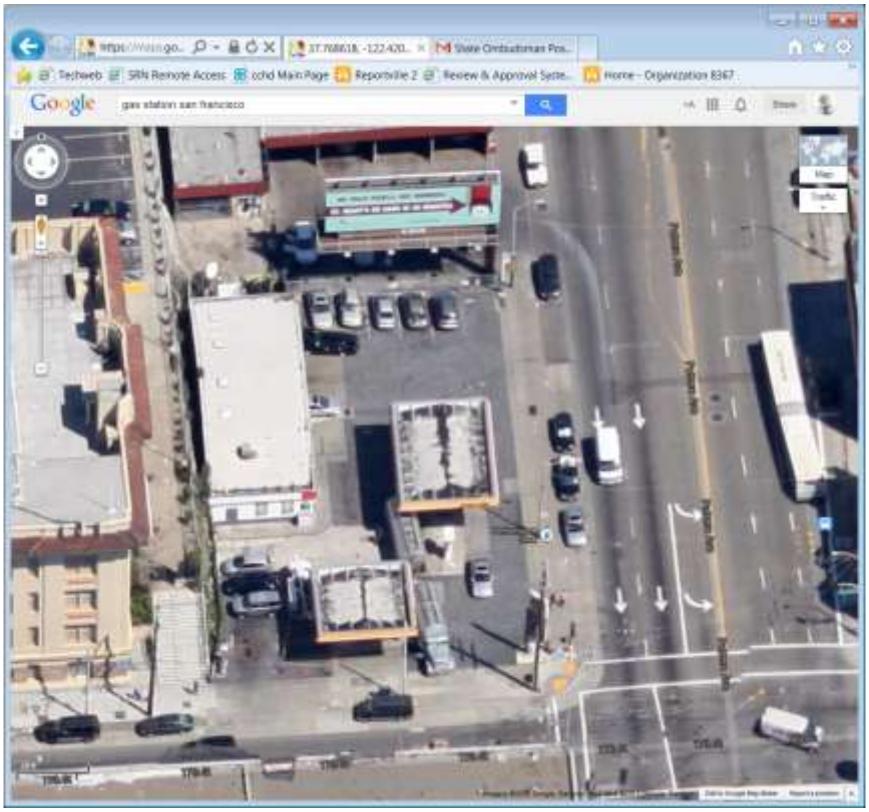
SF1#6


Techweb
SRN Remote Access
cchd Main Page
Reportville 2
Home - Organization 8367
Google
ARCO

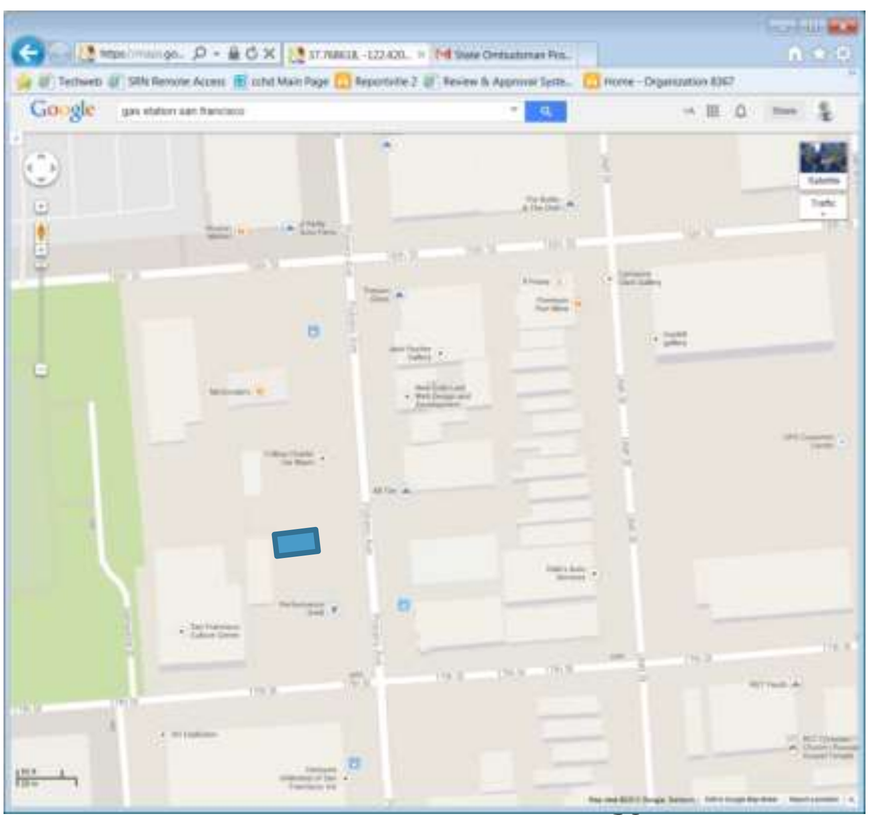
SF1 #6


Techweb
SRN Remote Access
cchd Main Page
Reportville 2
Home - Organization 8367
Google
ARCO® Gas Station
Shell Station Locator
Local Gas Stations

SF1 #7



SF1 #7

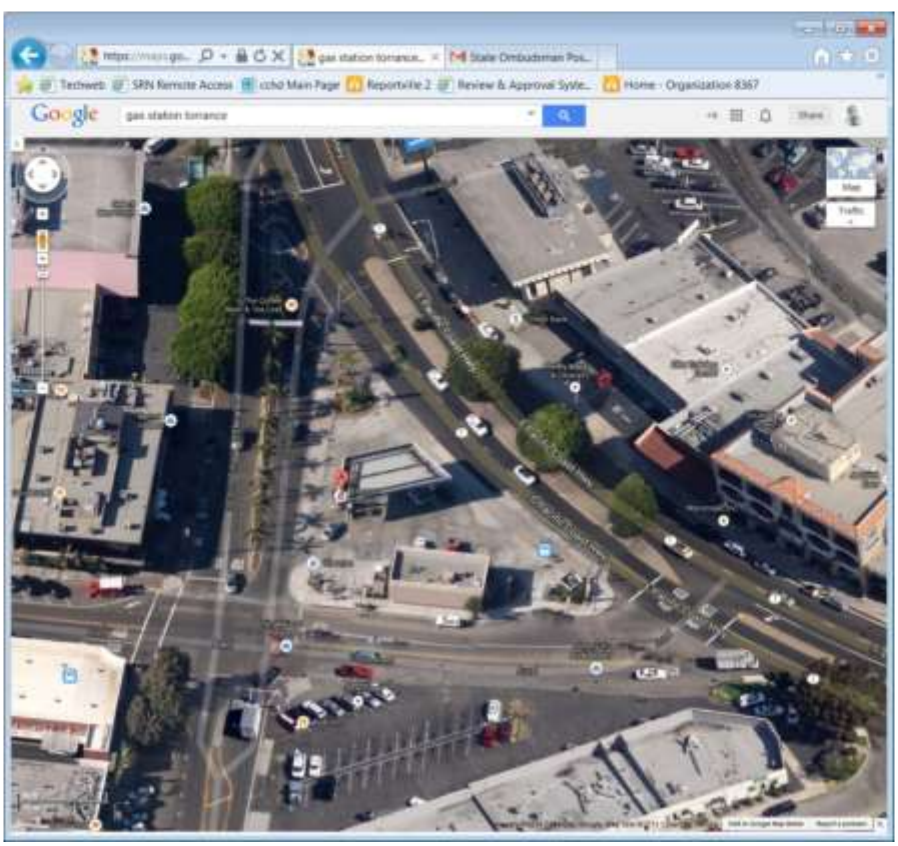


CEC Primary Area
Torrance (8 stations)

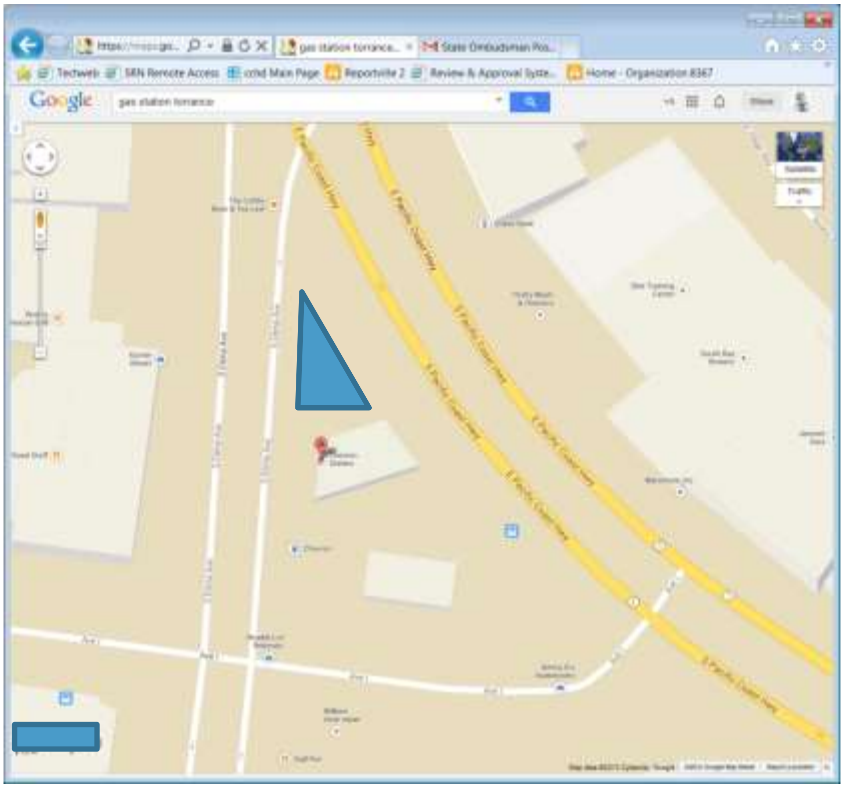
Torrance/Redondo Beach

6

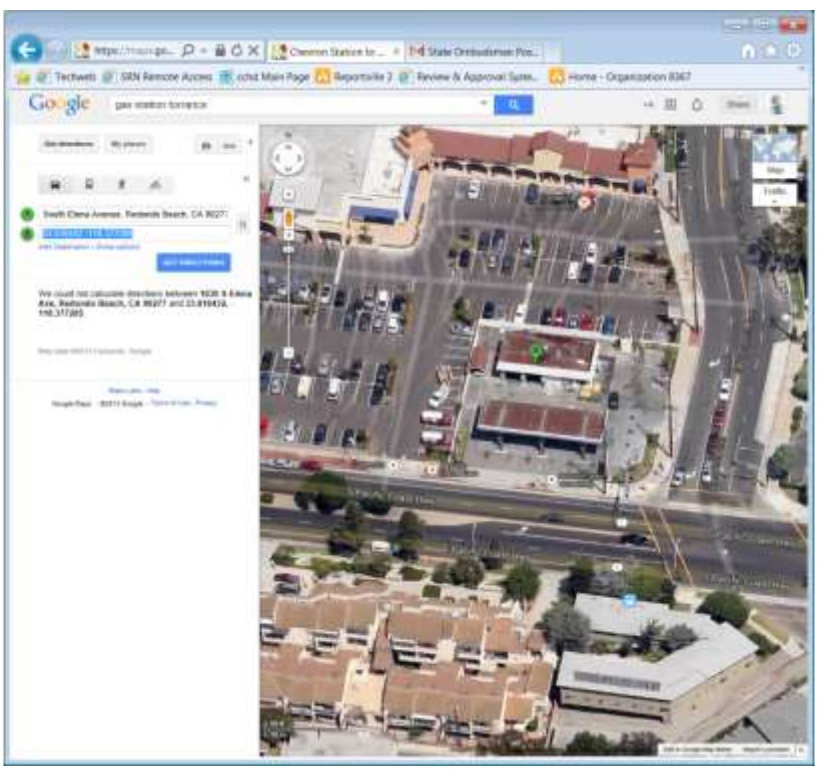
Torrance #1



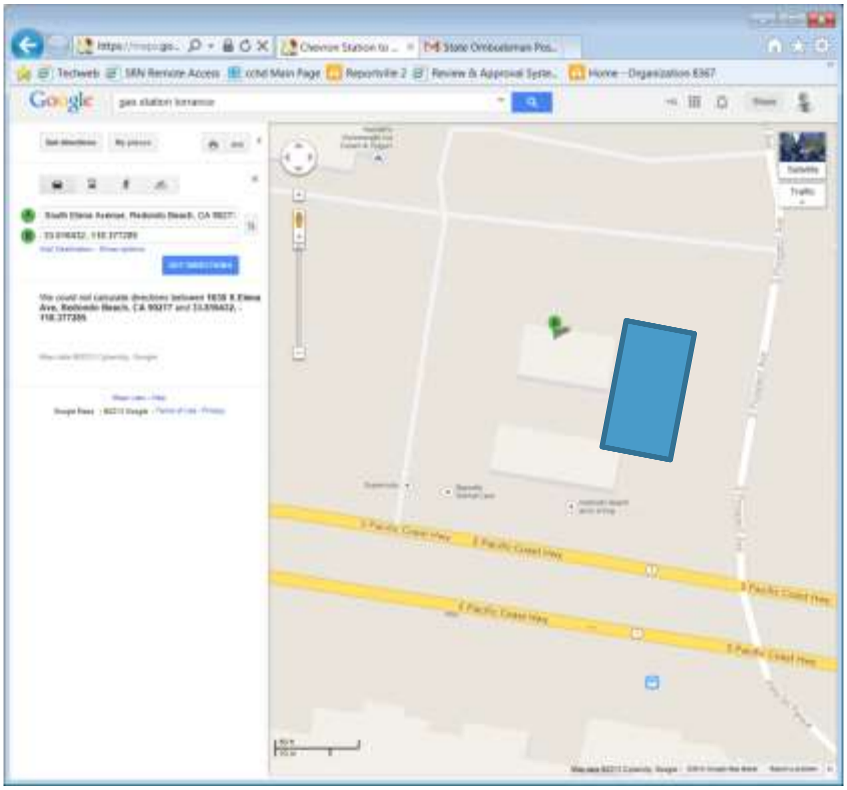
Torrance #1



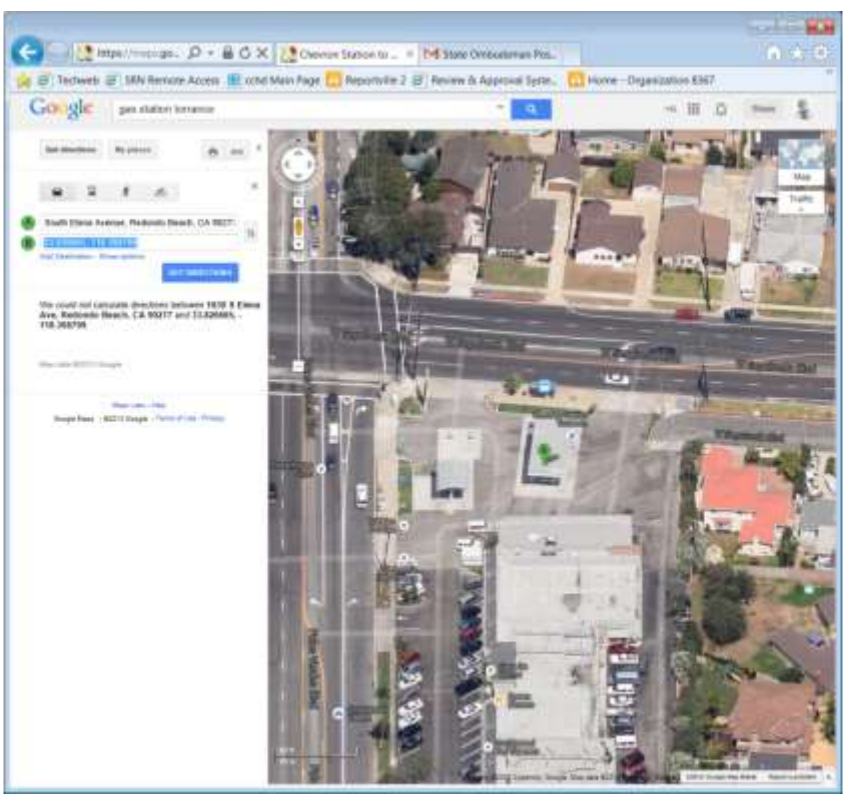
Torrance #2



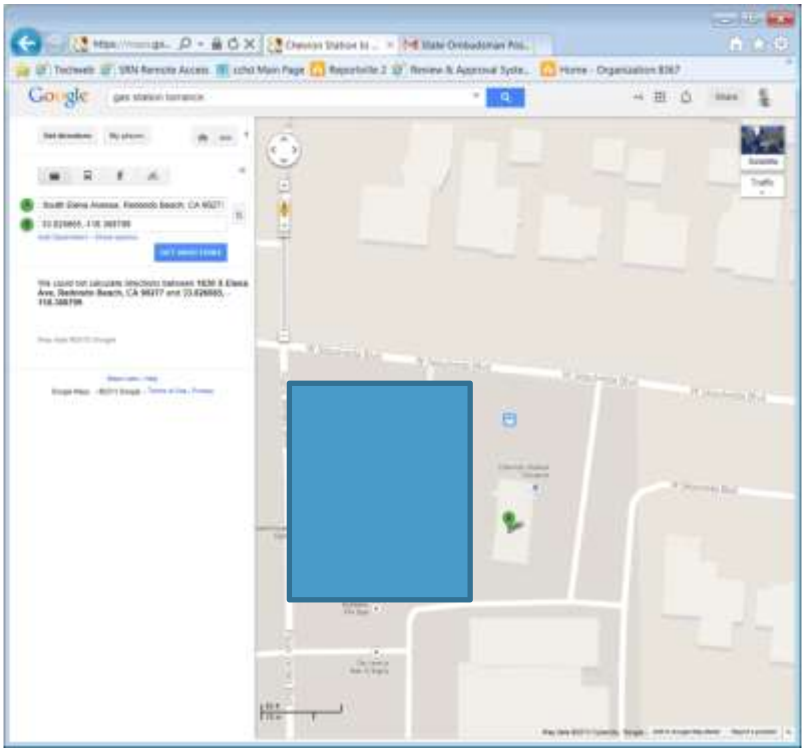
Torrance #2



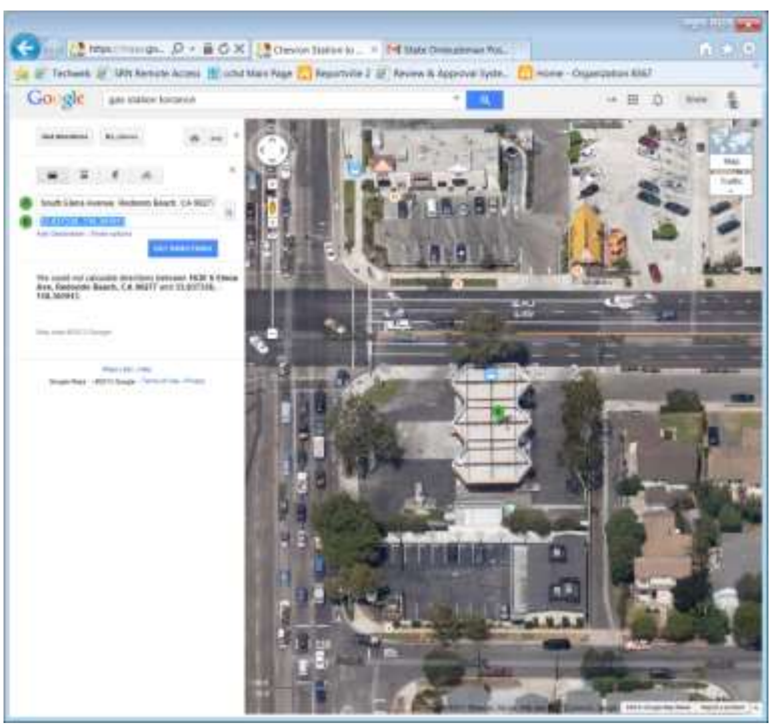
Torrance #3



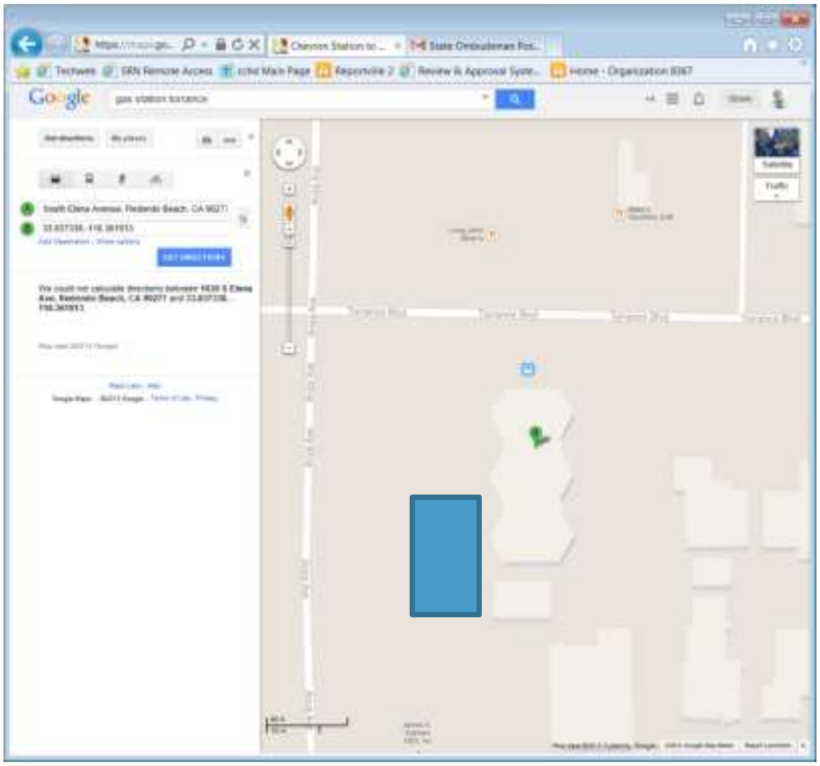
Torrance #3



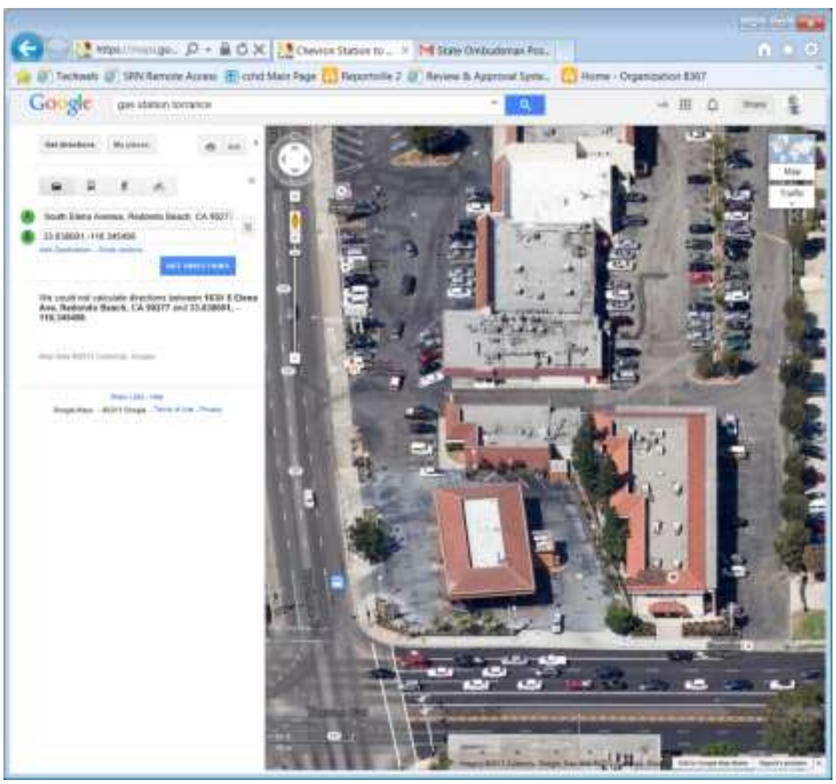
Torrance #4



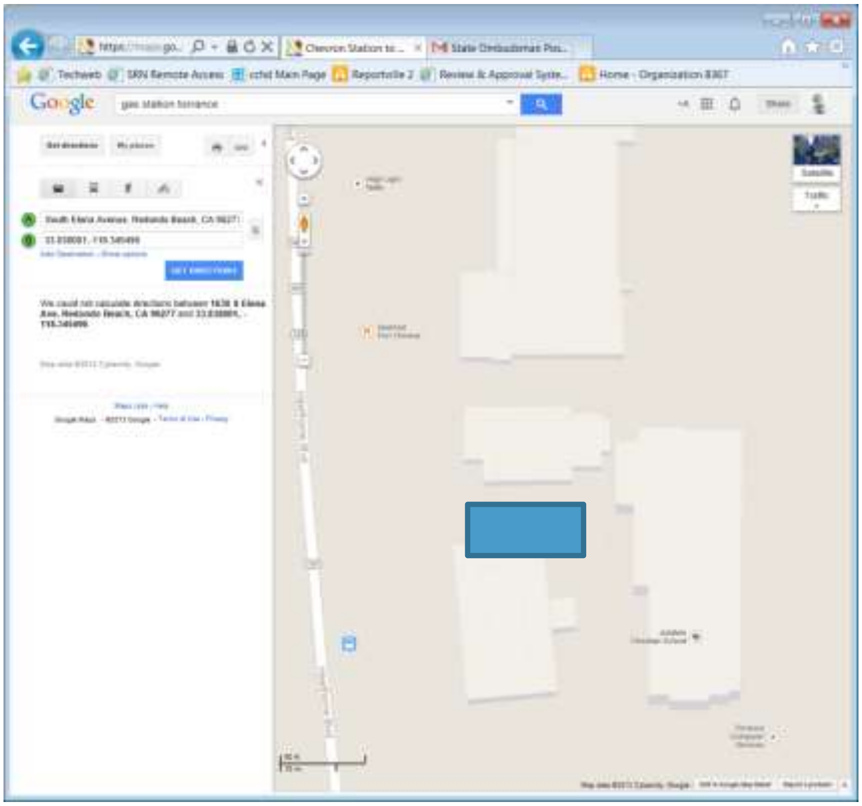
Torrance #4



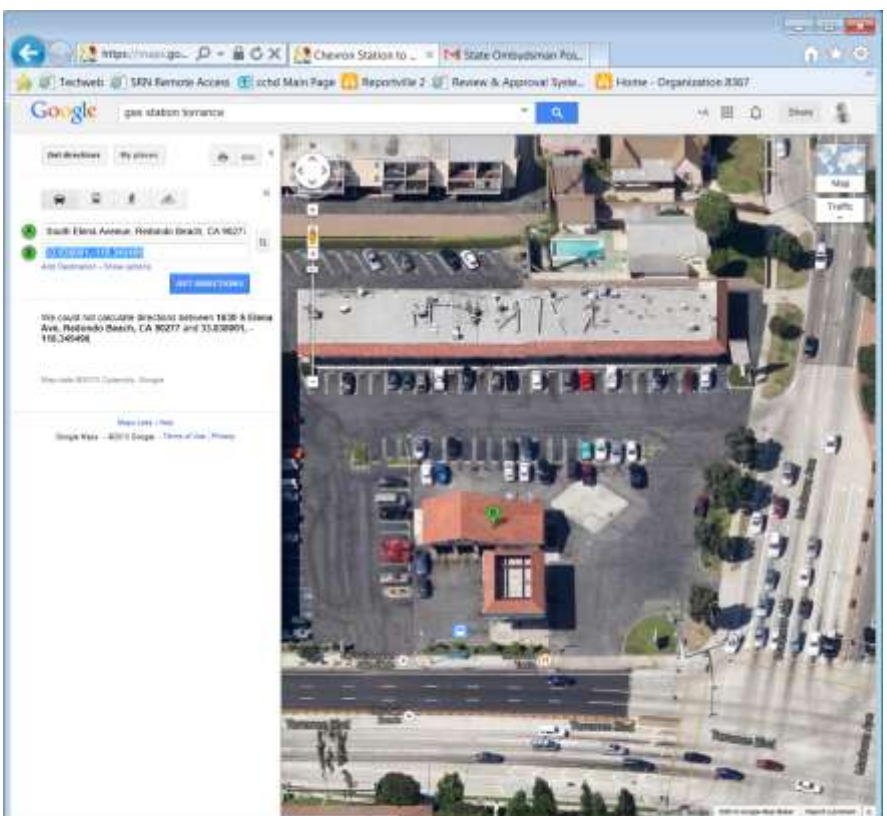
Torrance #5



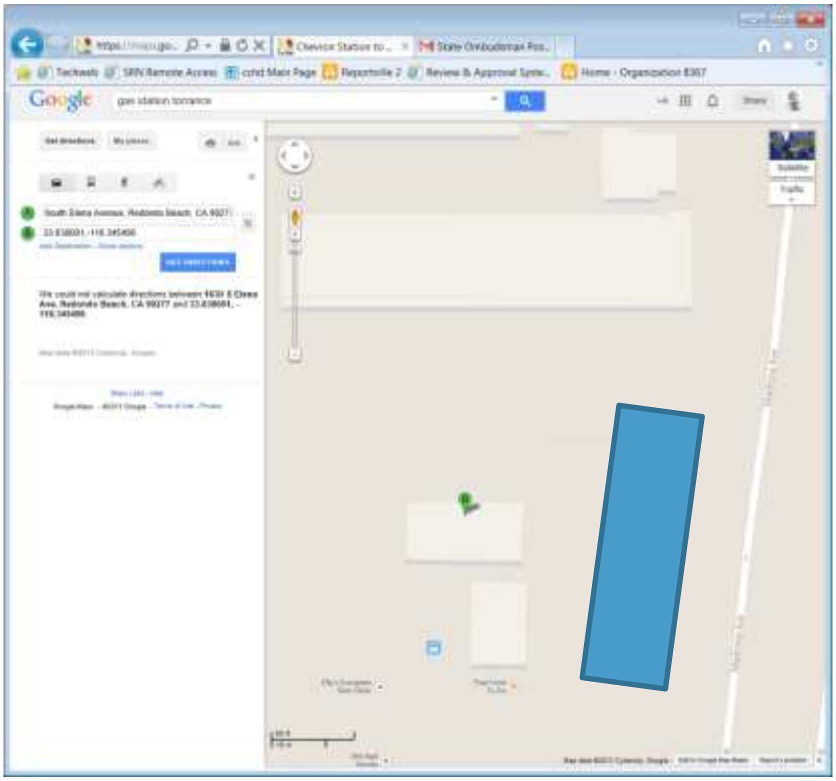
Torrance #5



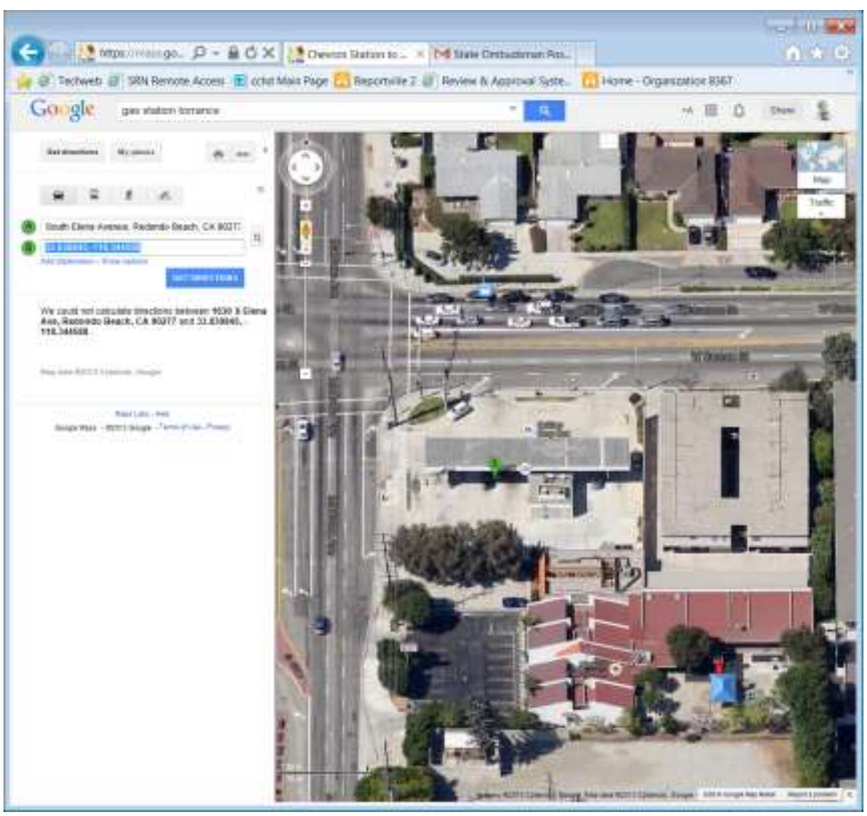
Torrance #6



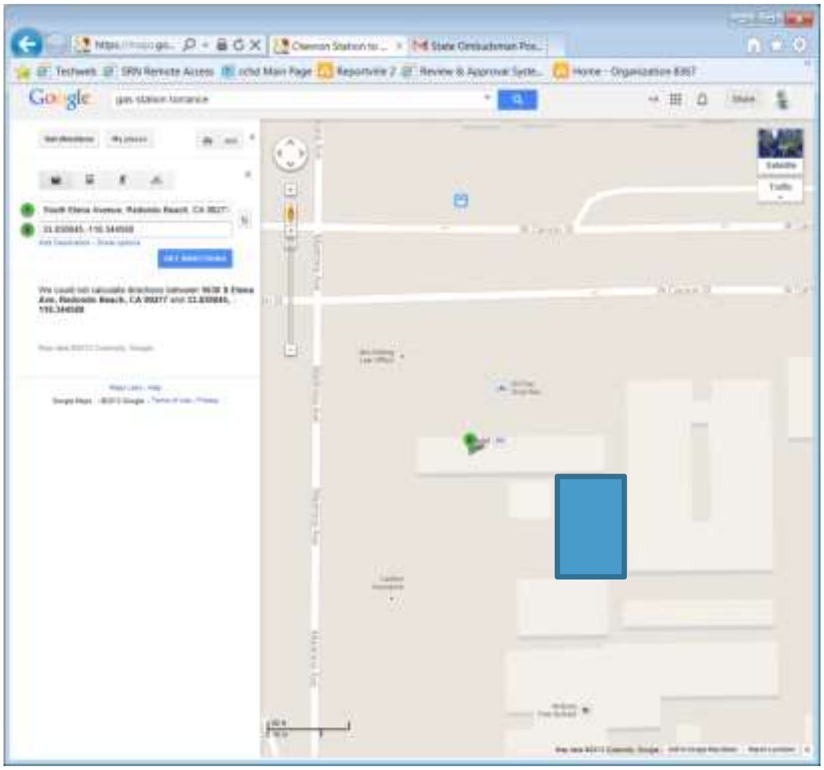
Torrance #6



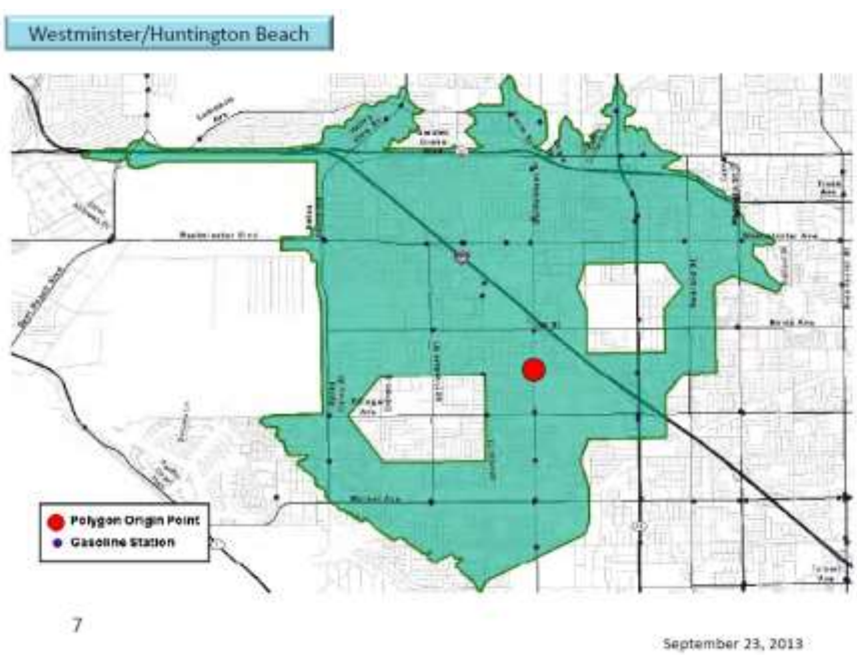
Torrance #7



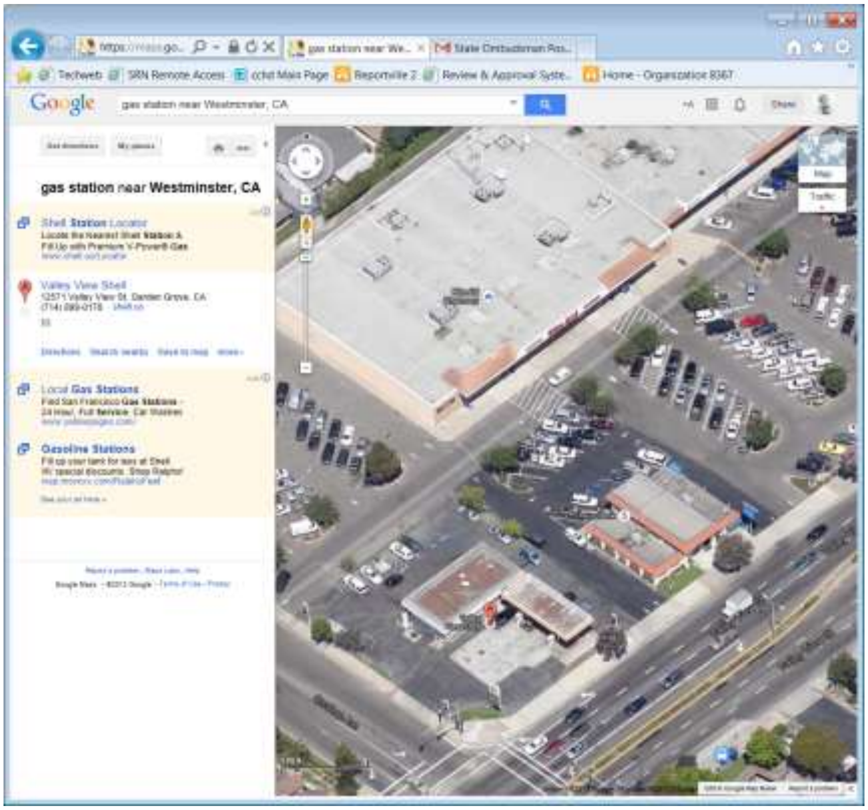
Torrance #7



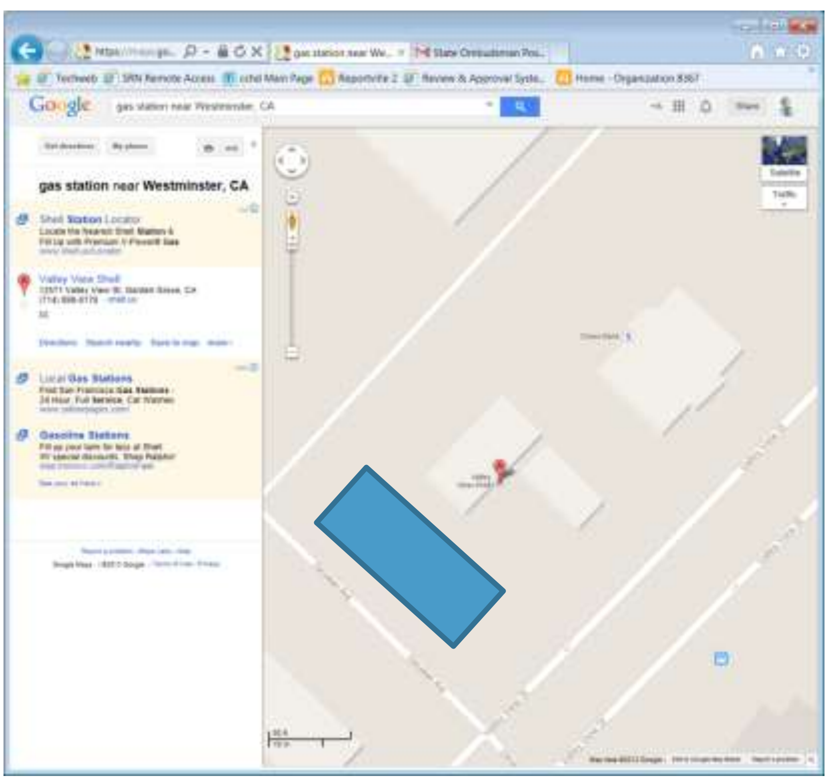
CEC Primary Area Westminster (37 stations)



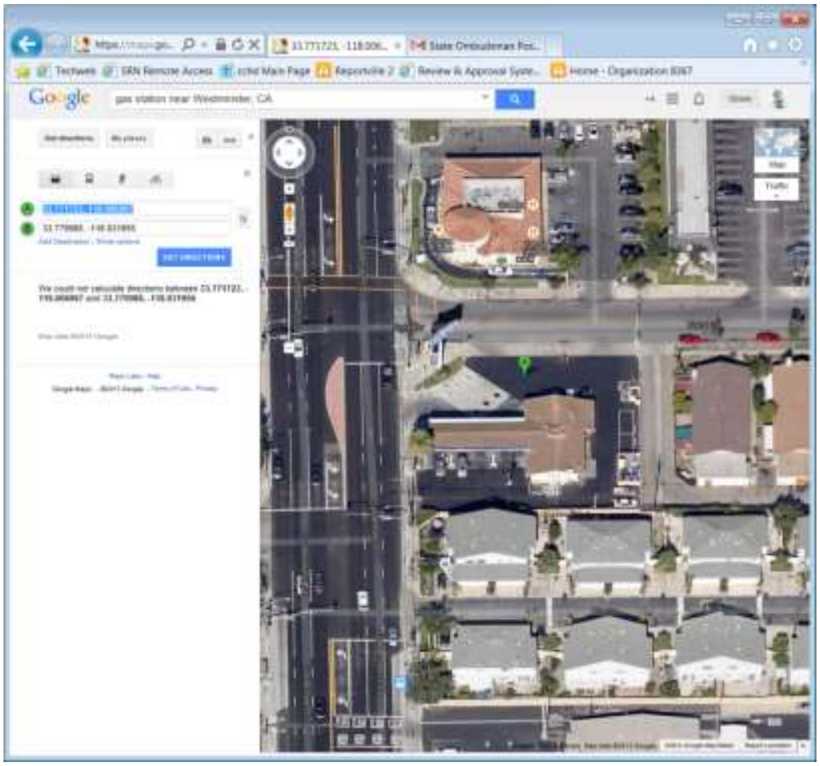
Westminster #1



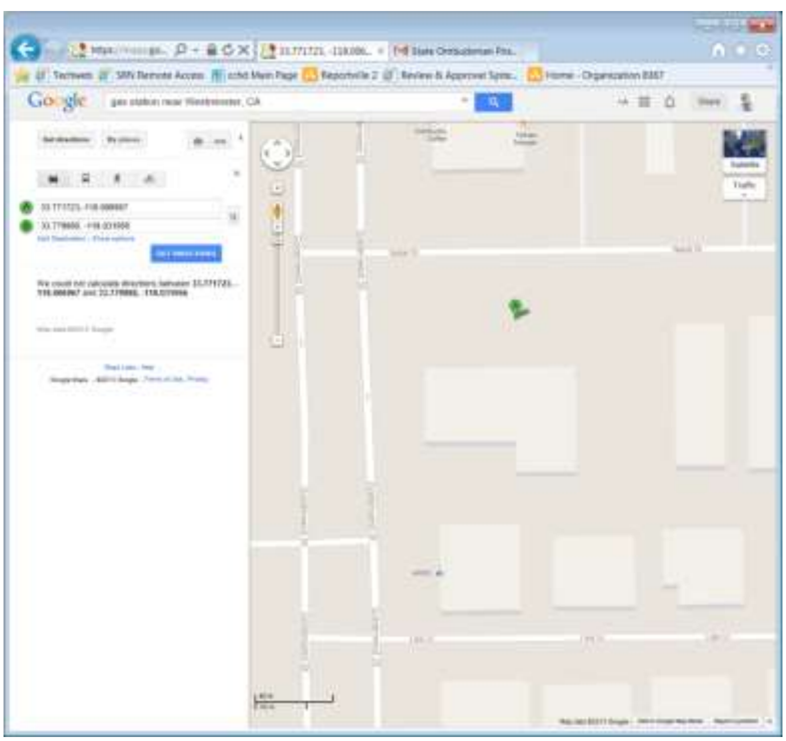
Westminster #1



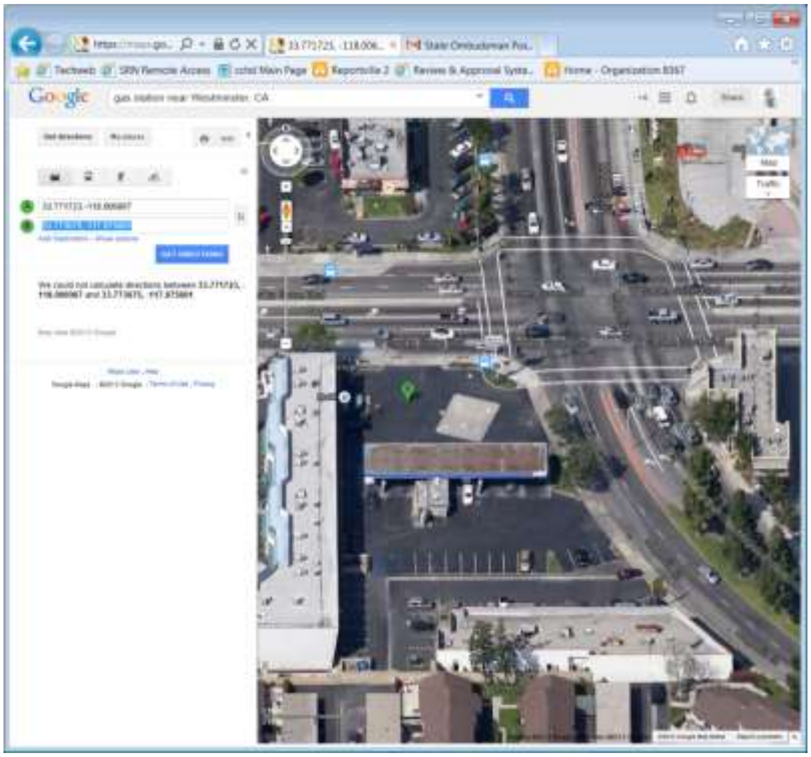
Westminster #2



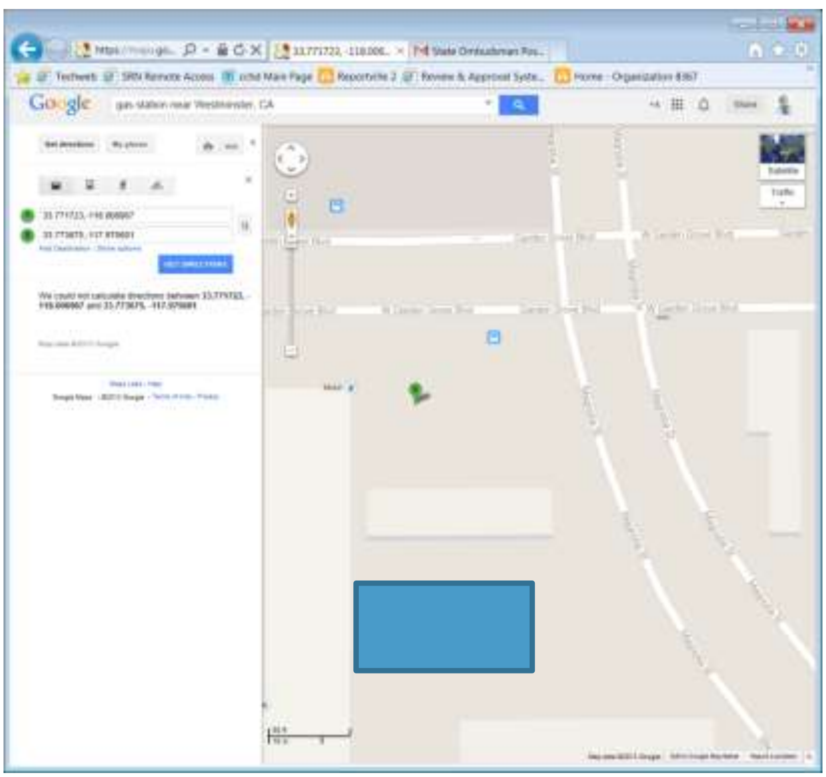
Westminster #2



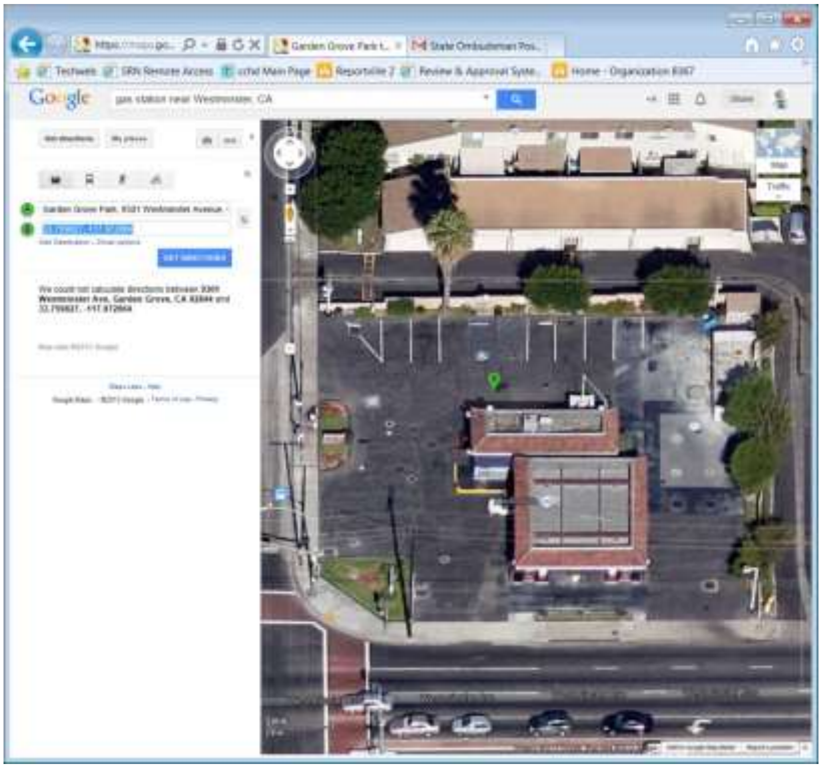
Westminster #3



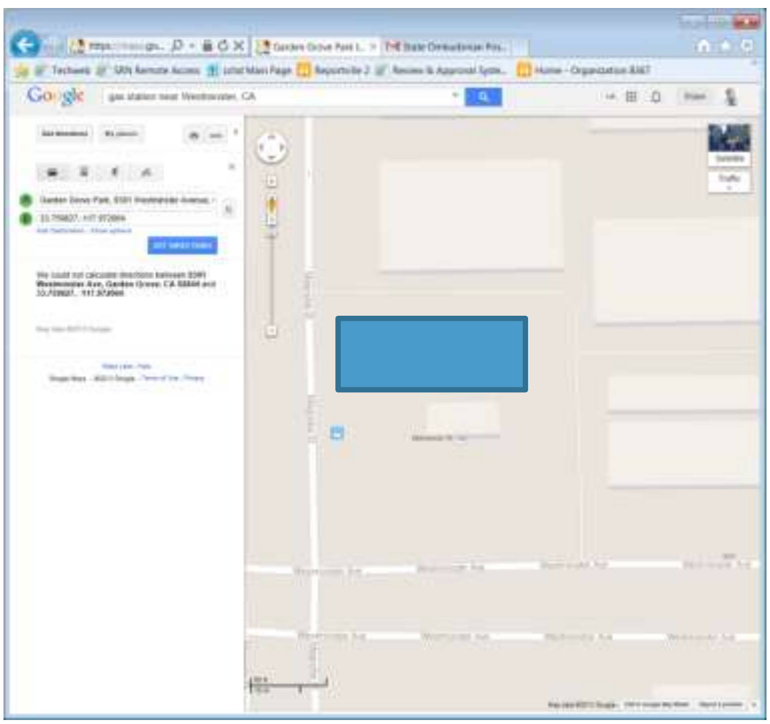
Westminster #3



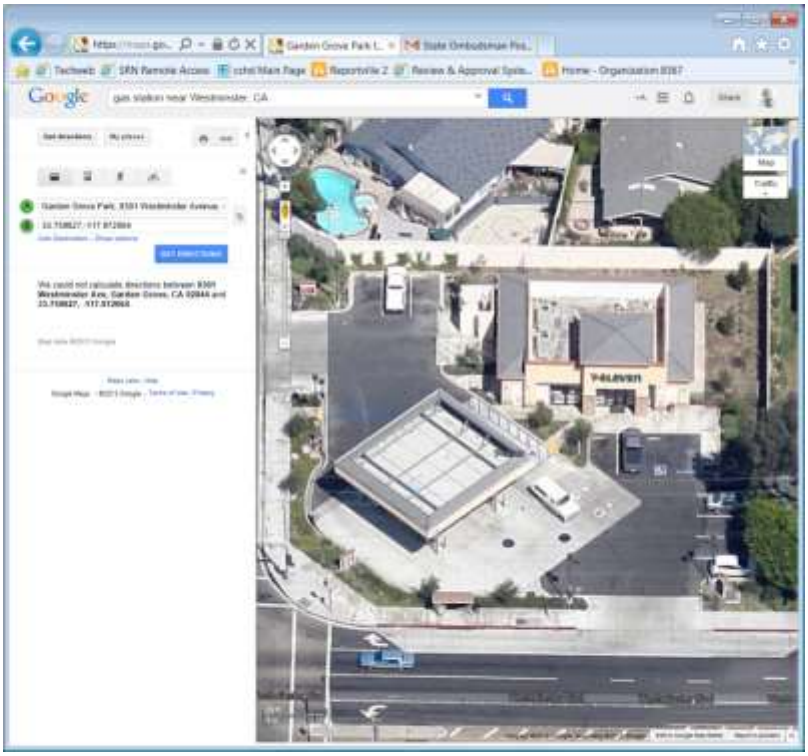
Westminster #4



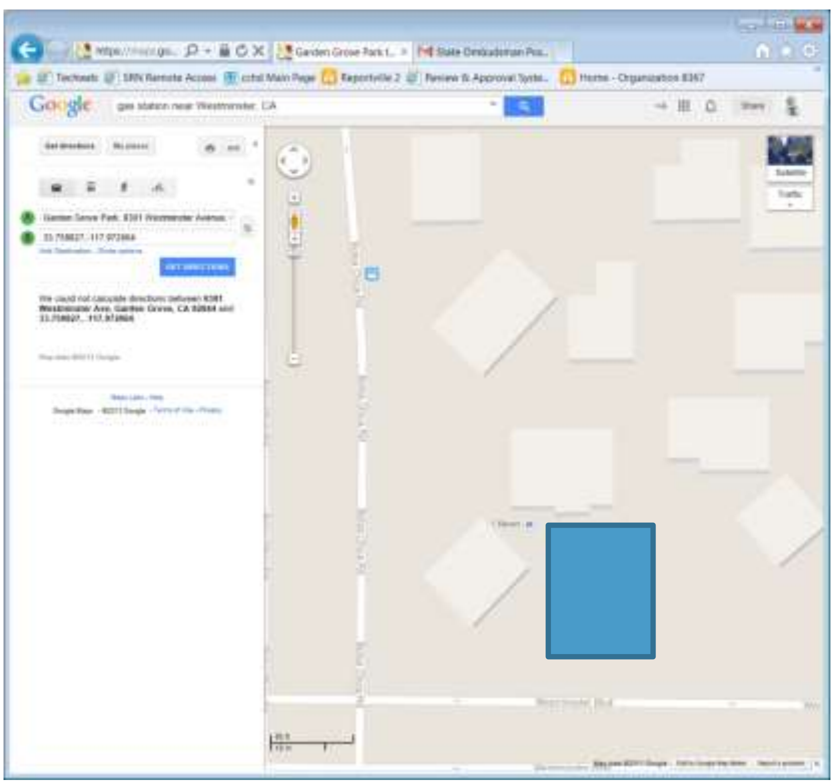
Westminster #4



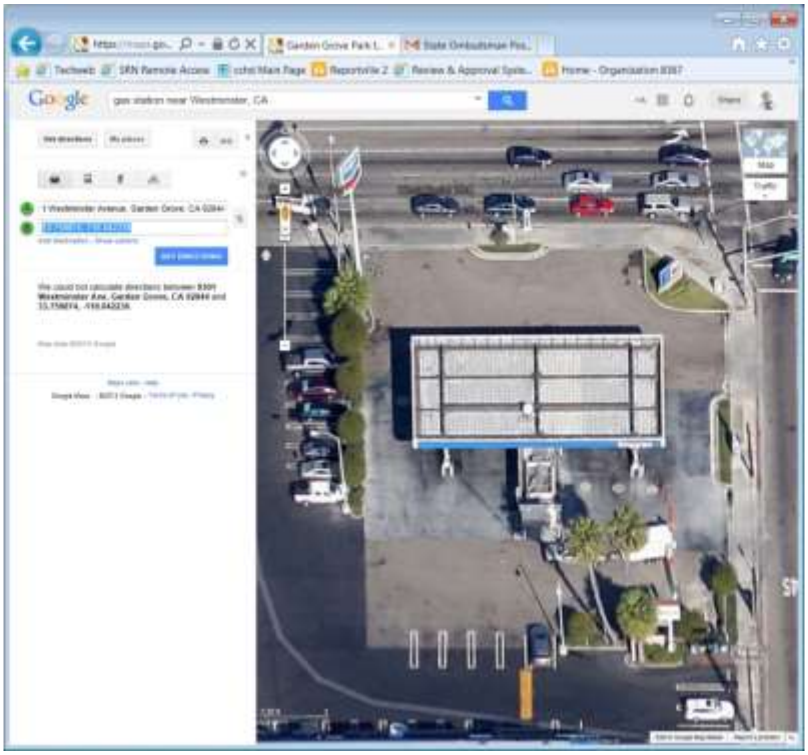
Westminster #5



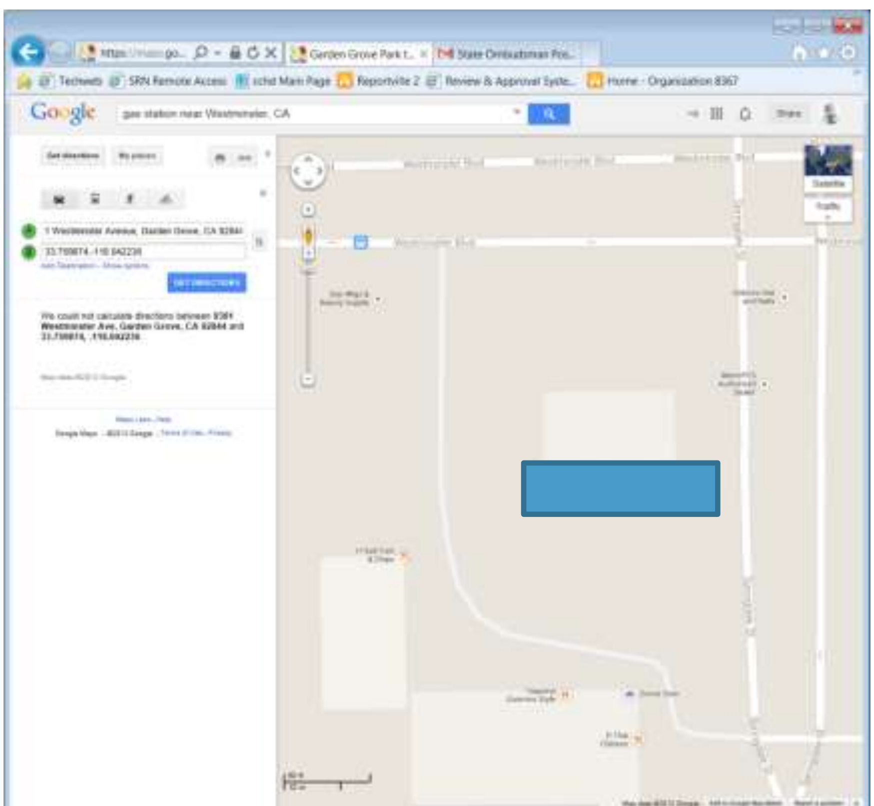
Westminster #5



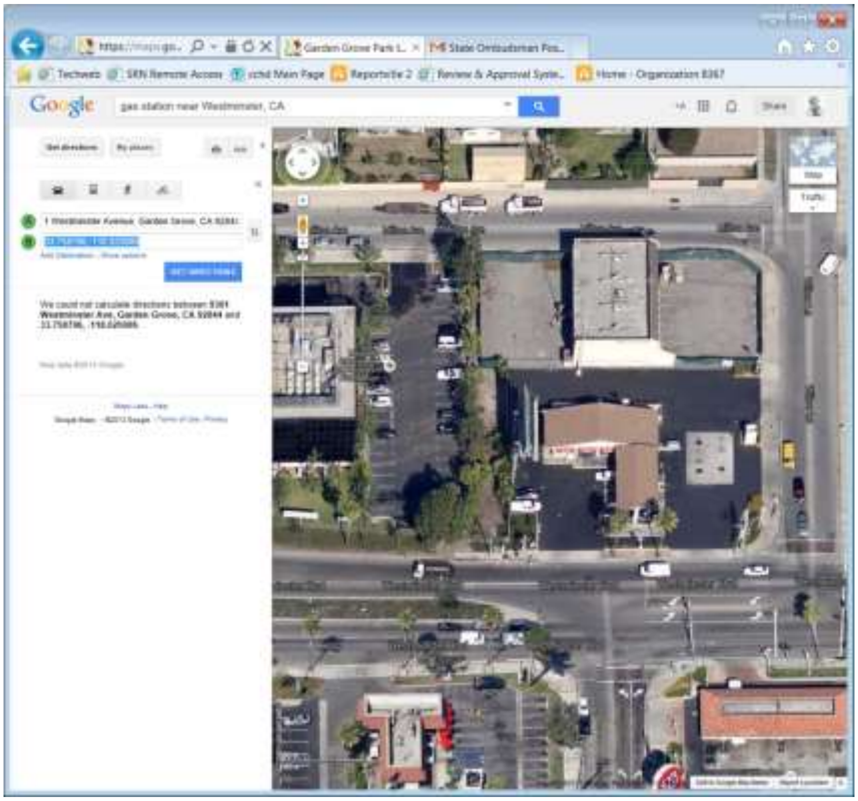
Westminster #6



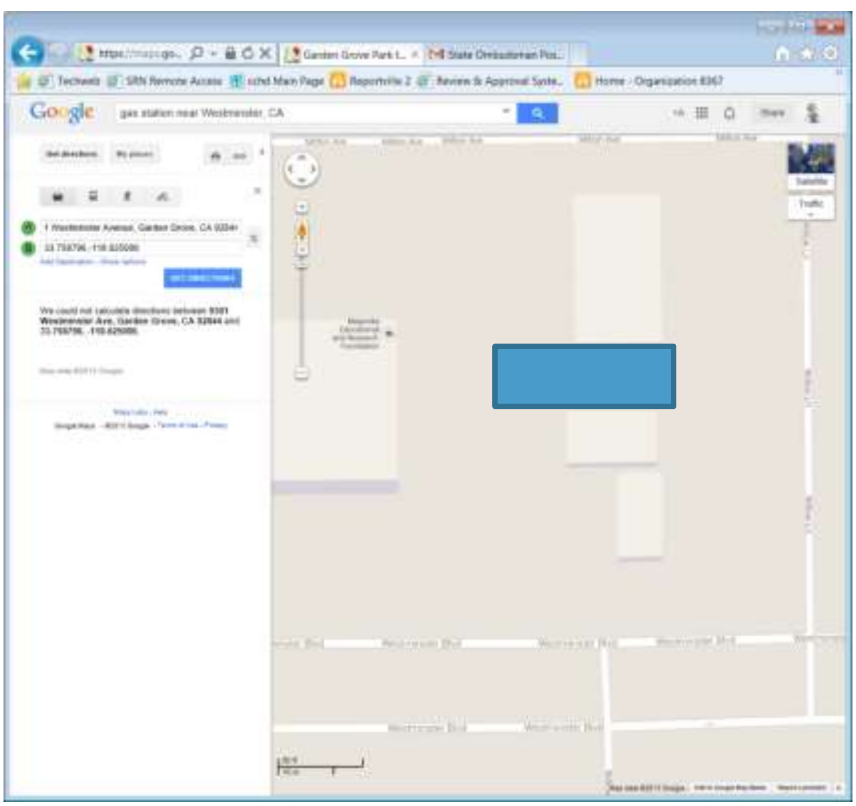
Westminster #6



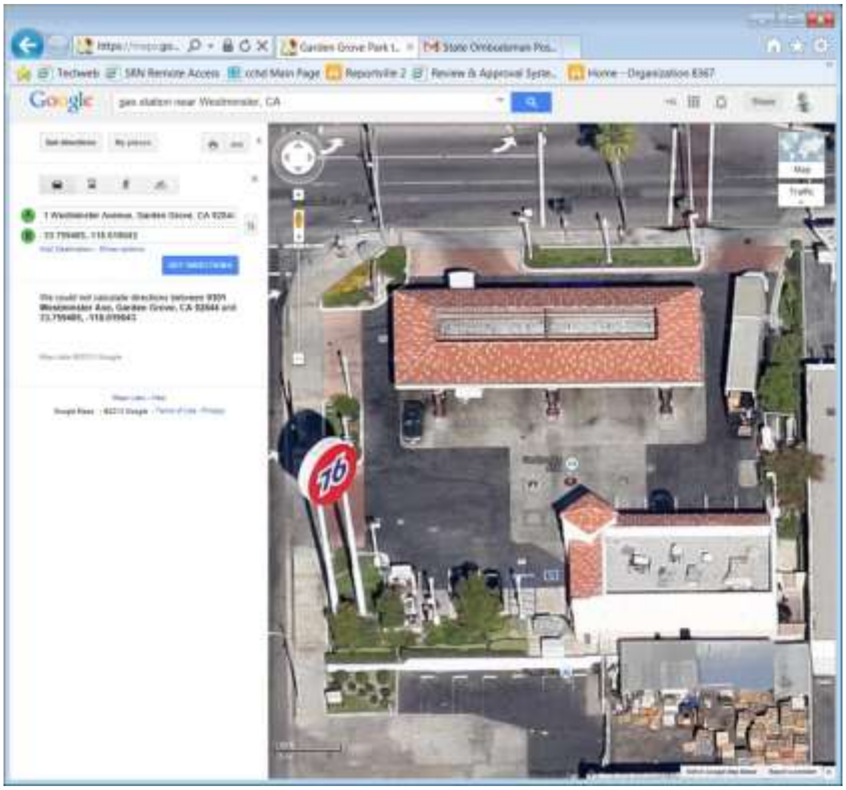
Westminster #7



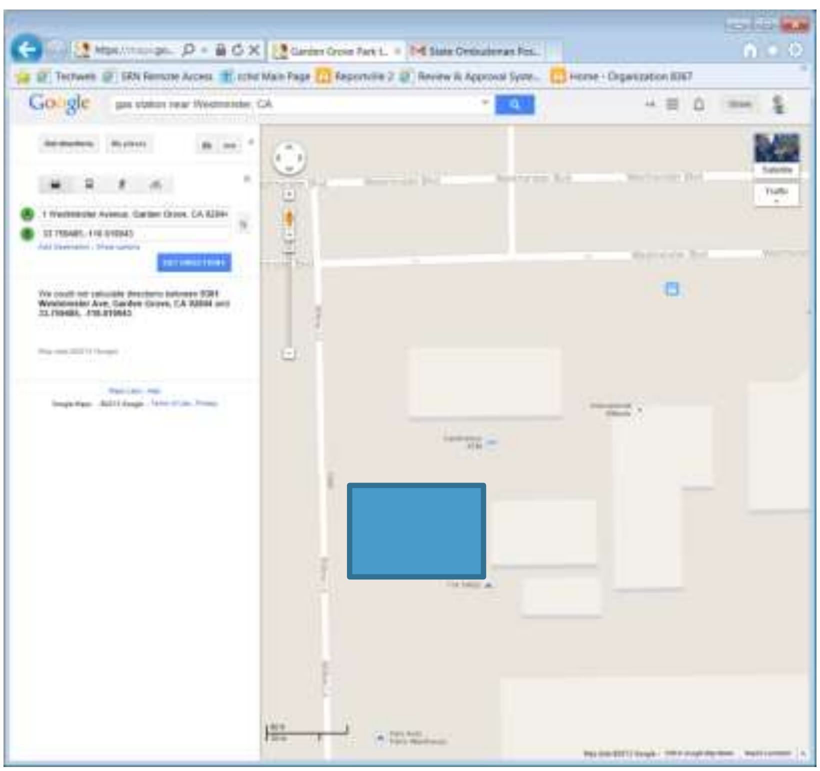
Westminster #7



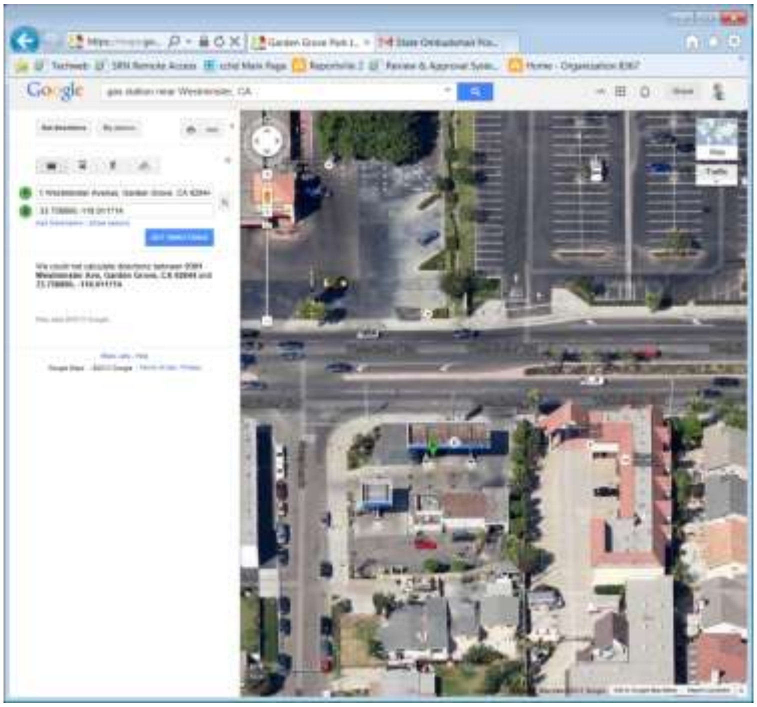
Westminster #8



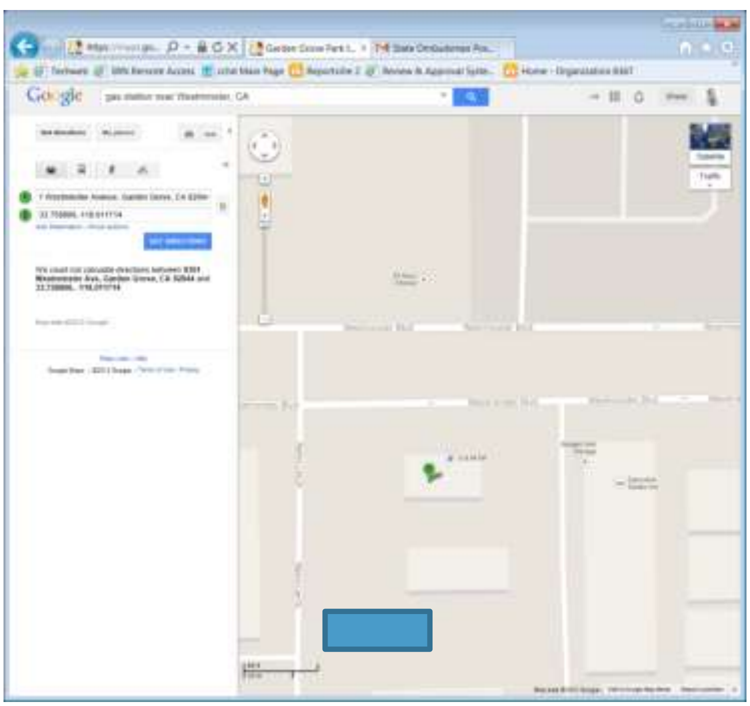
Westminster #8



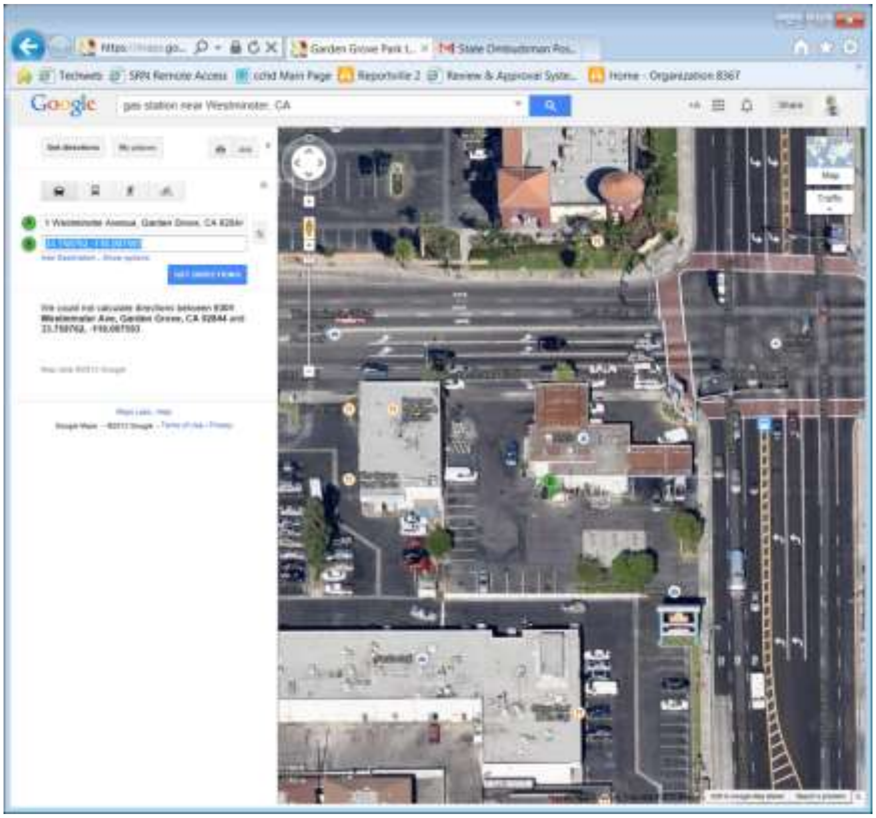
Westminster #9



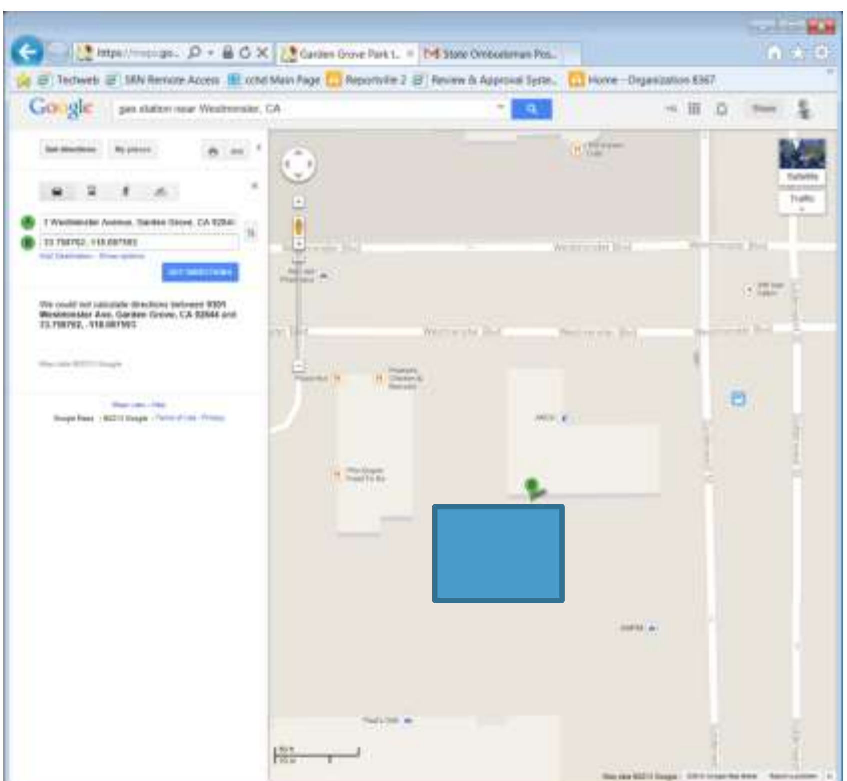
Westminster #9



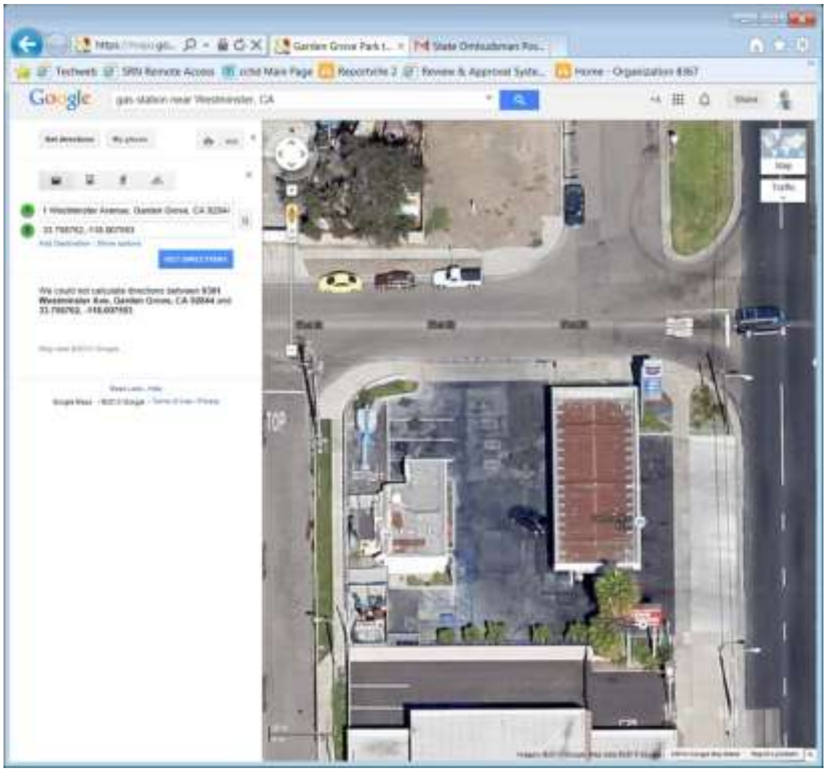
Westminster #10



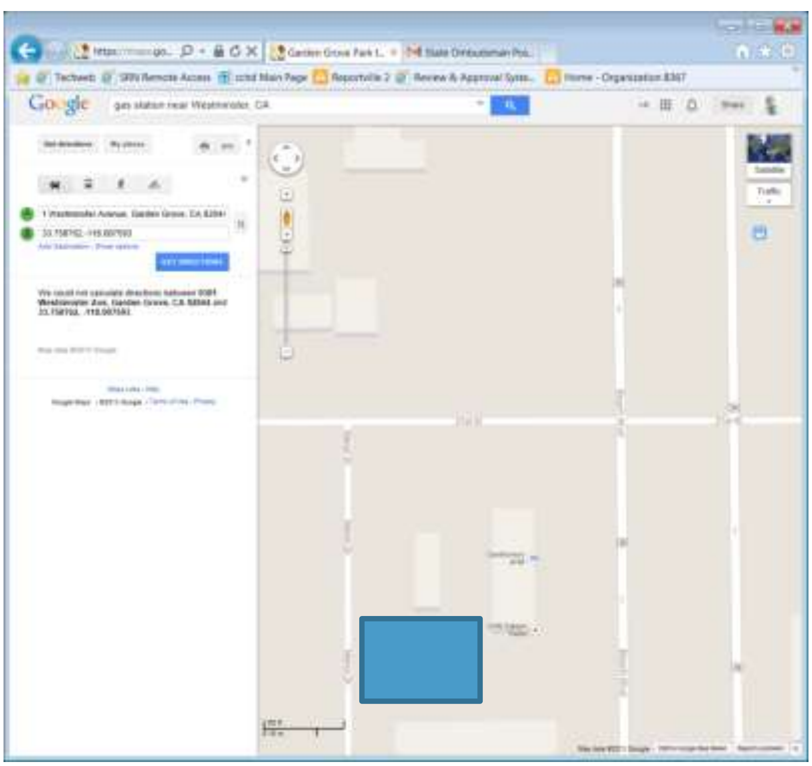
Westminster #10



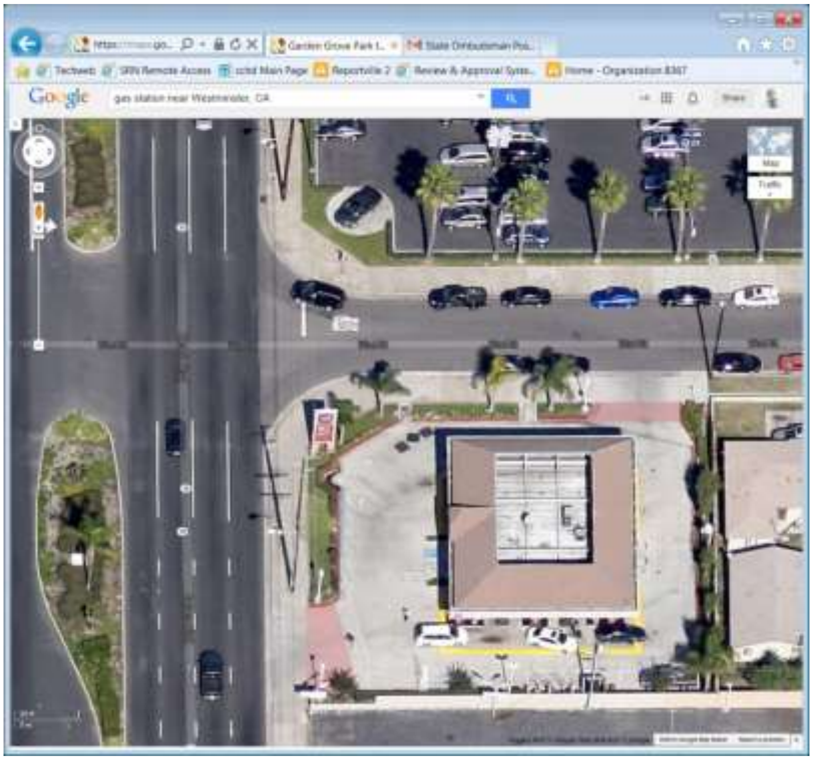
Westminster #11



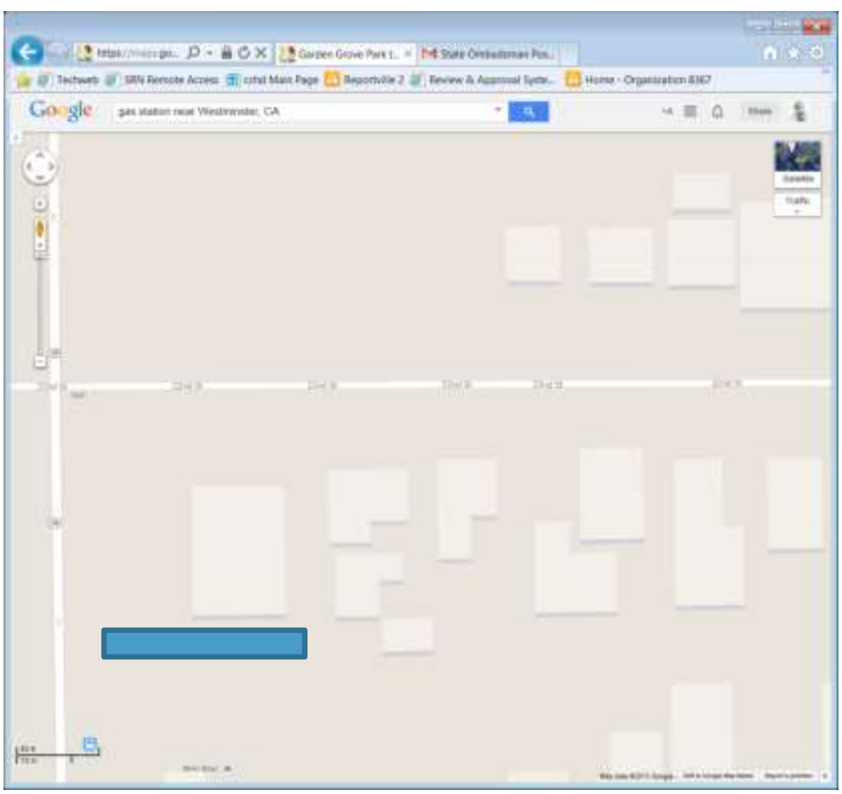
Westminster #11



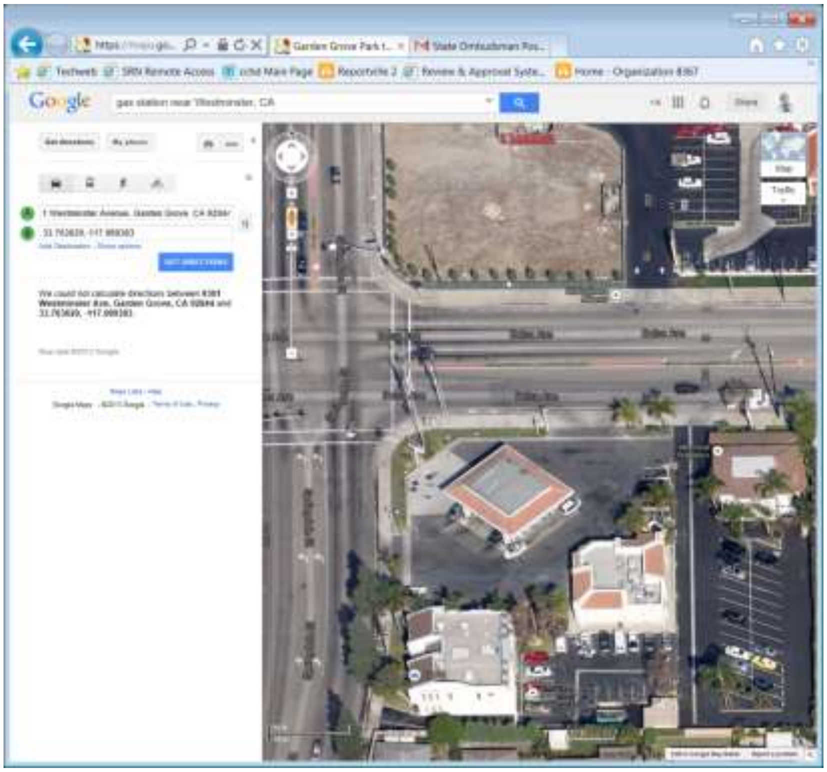
Westminster #12



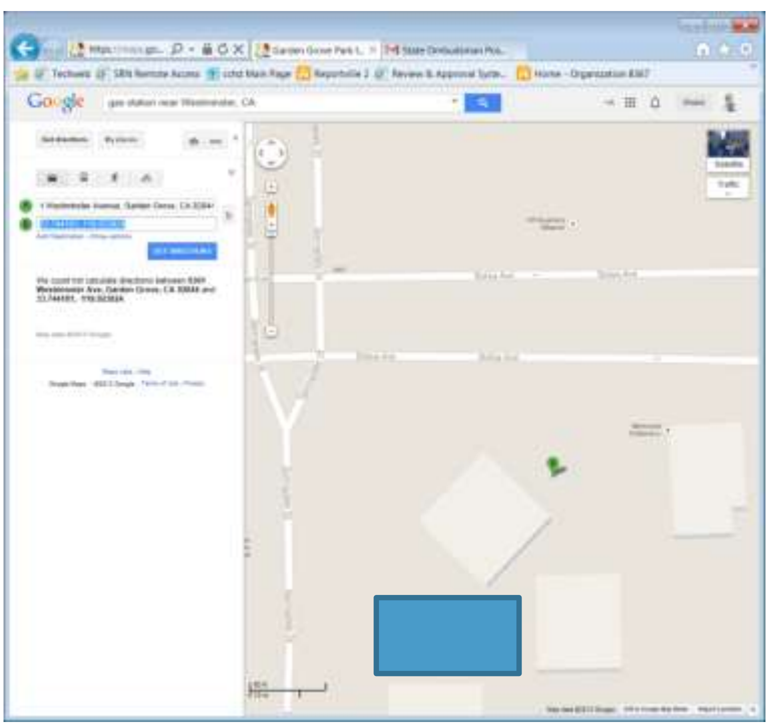
Westminster #12



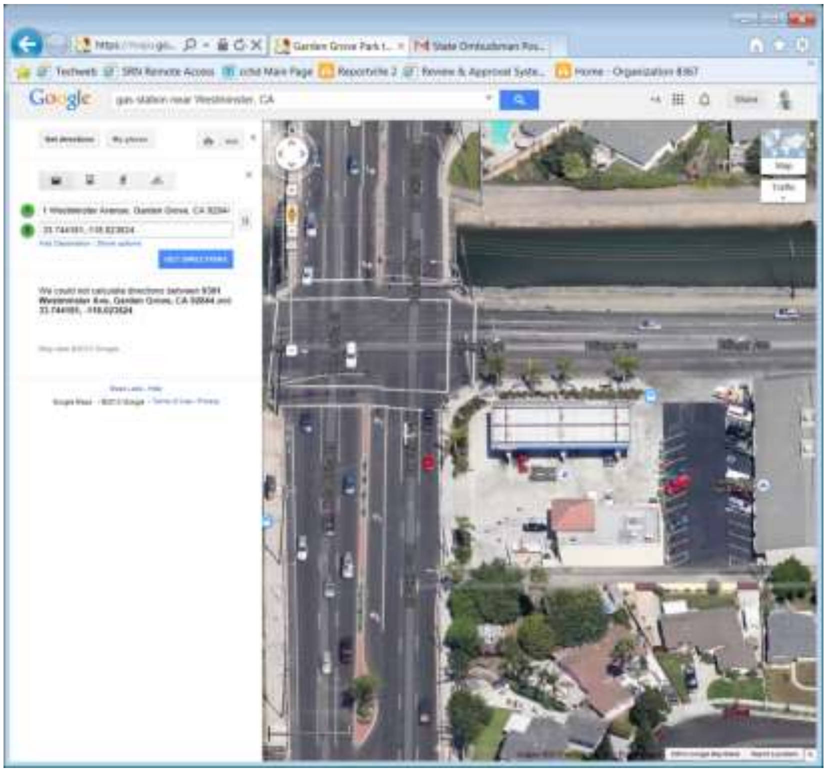
Westminster #13



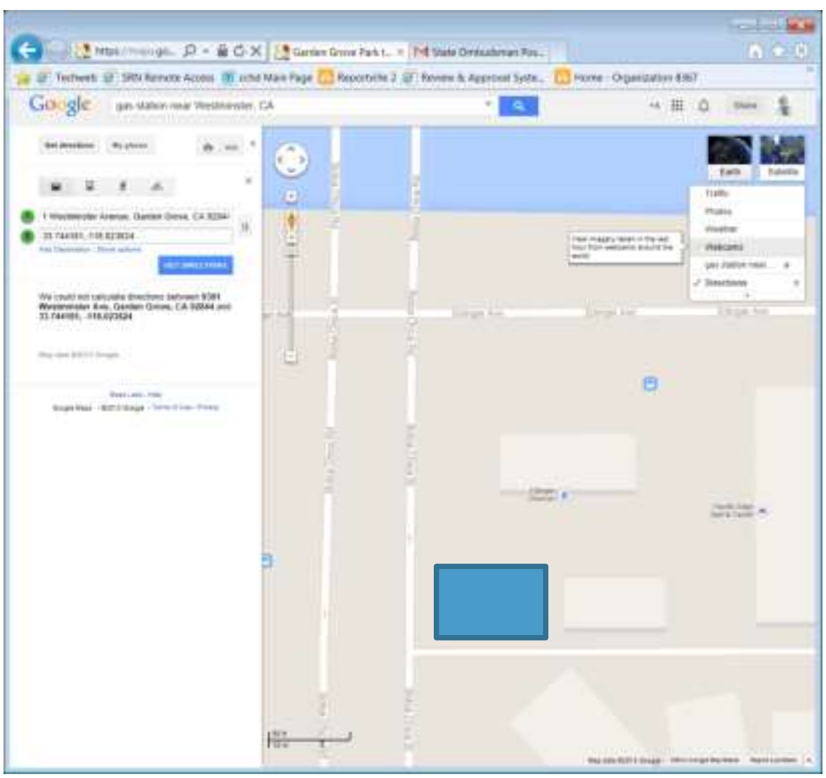
Westminster #13



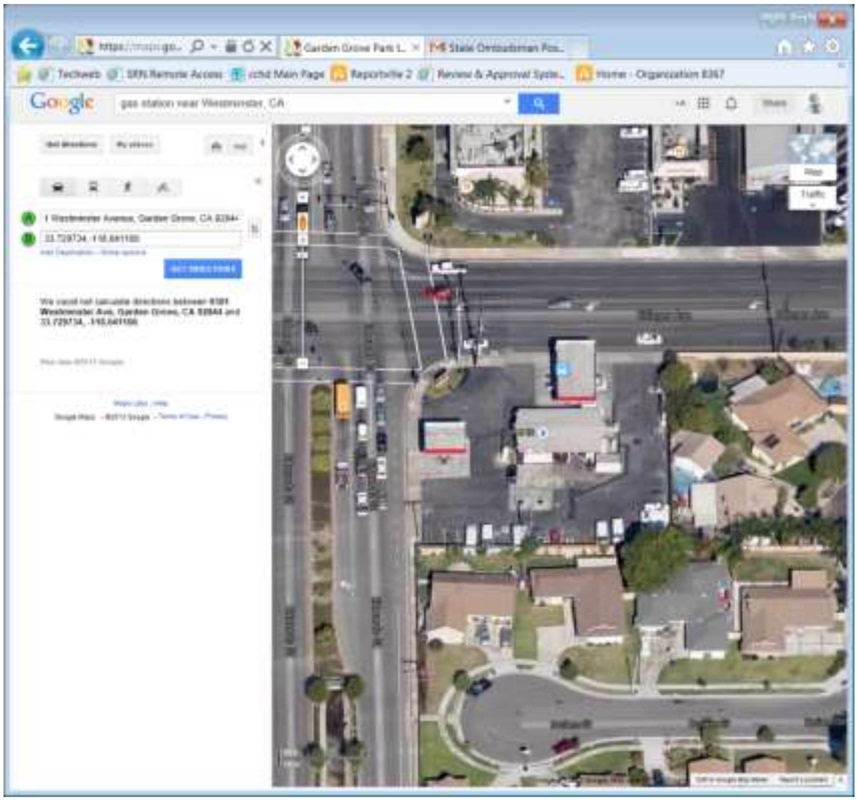
Westminster #14



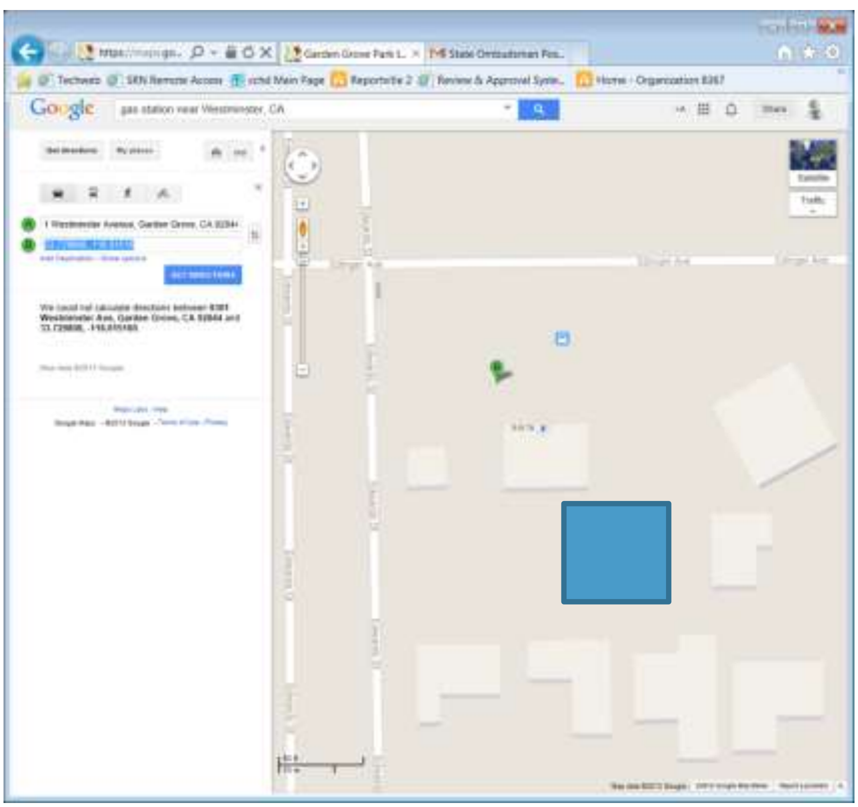
Westminster #14



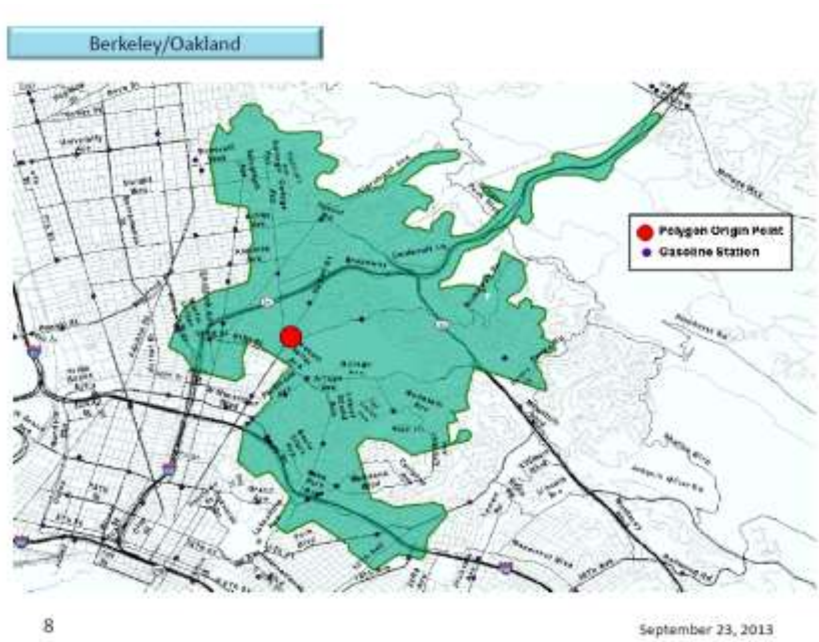
Westminster #15



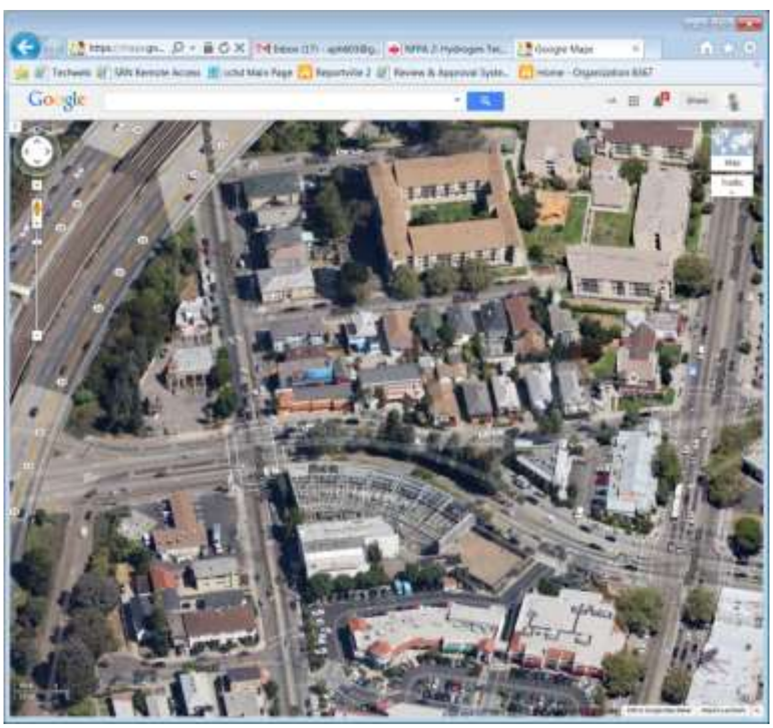
Westminster #15



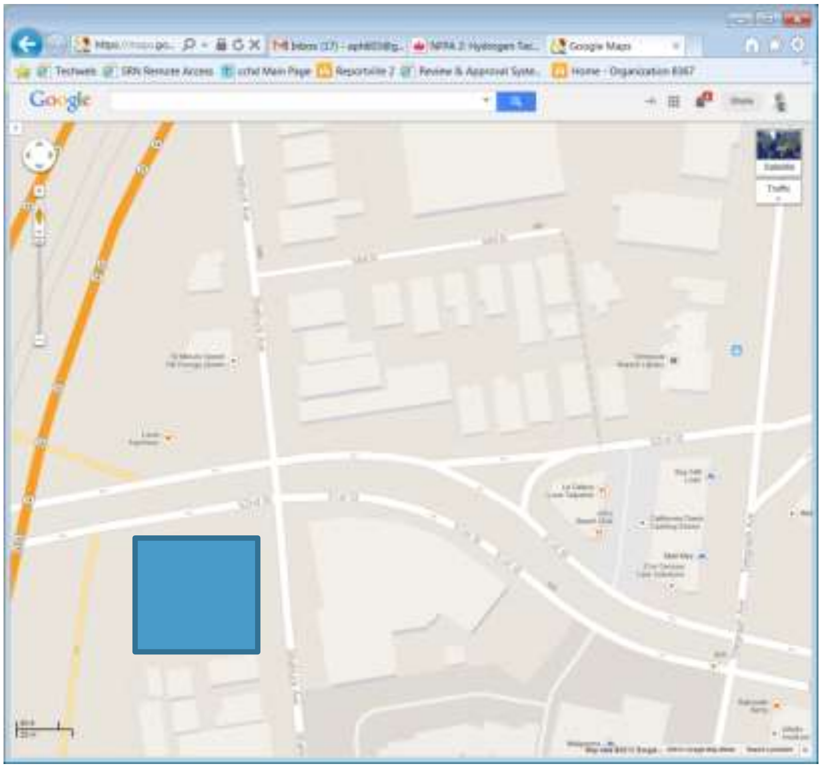
CEC Secondary Area
Oakland (23 stations)



Oakland #1



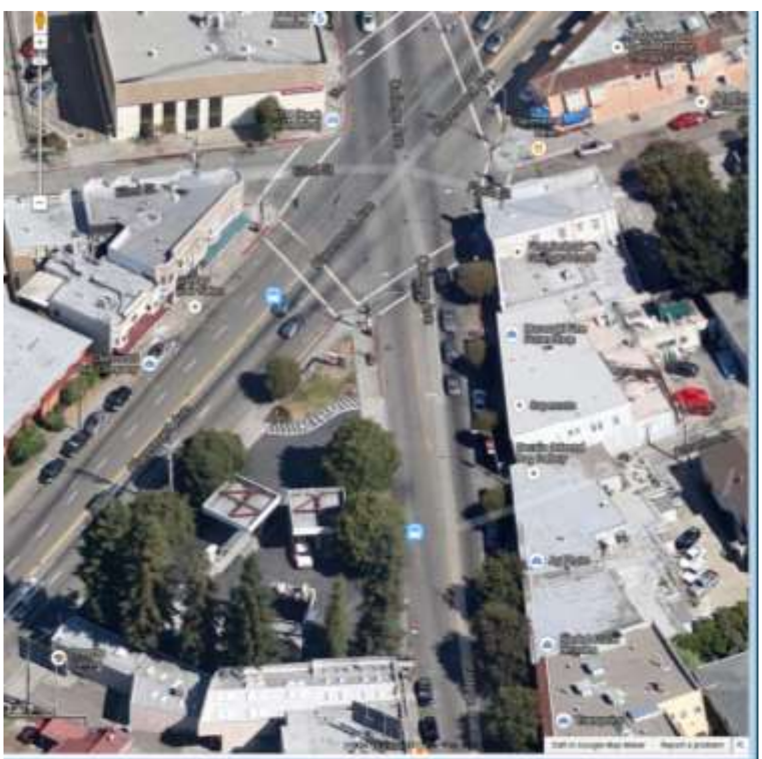
Oakland #1



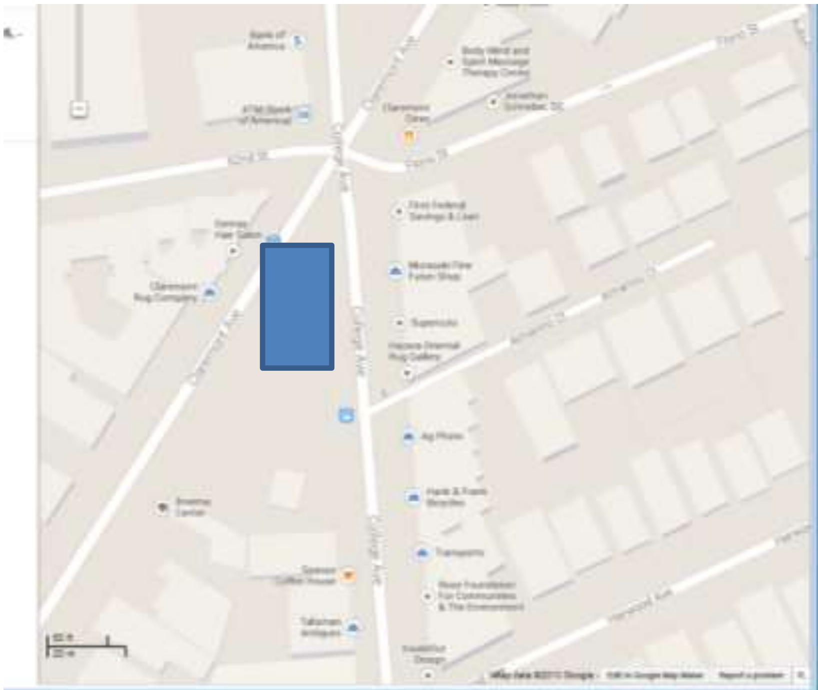
Oakland #2

Oakland #1

Oakland #3

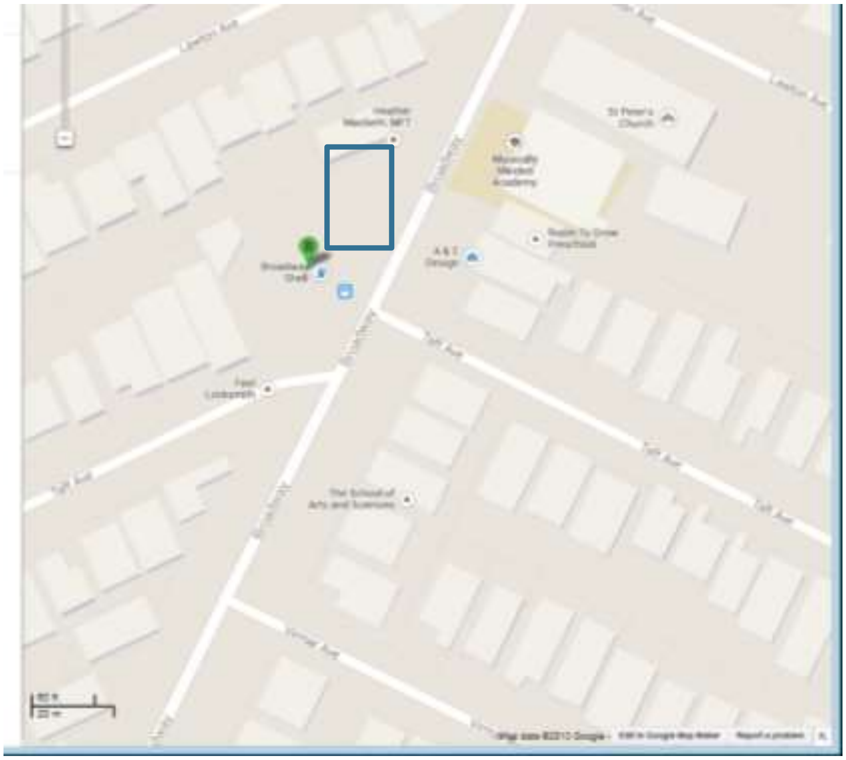


Oakland #3



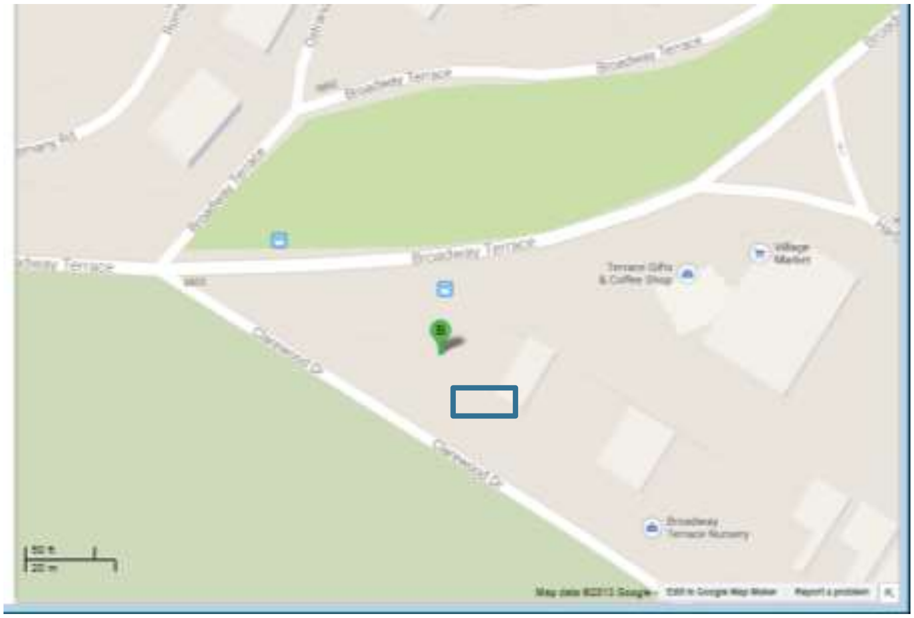
Oakland #4

Oakland #4



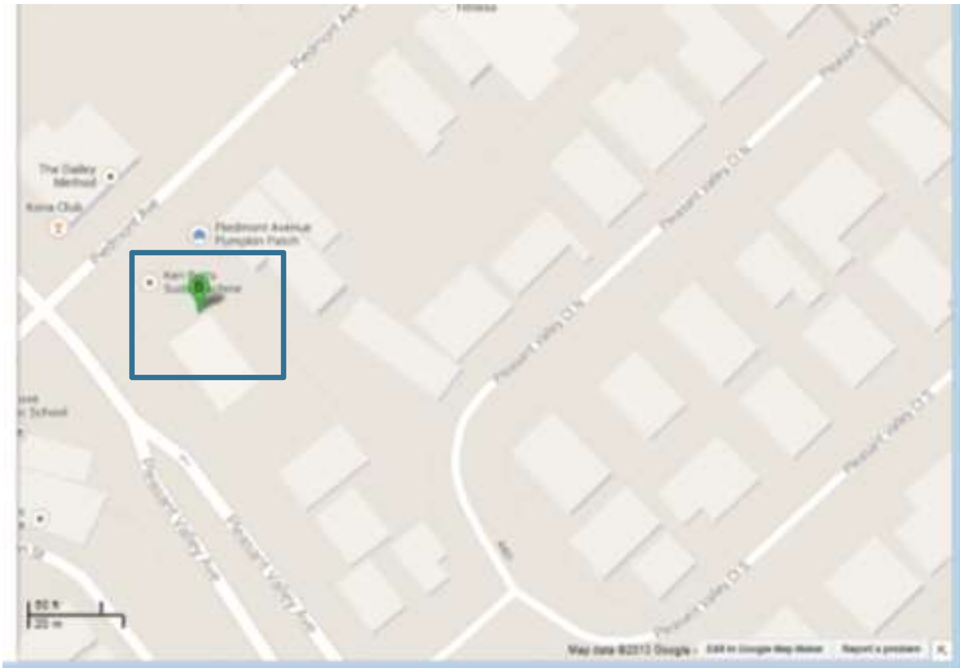
Oakland #5

Oakland #5

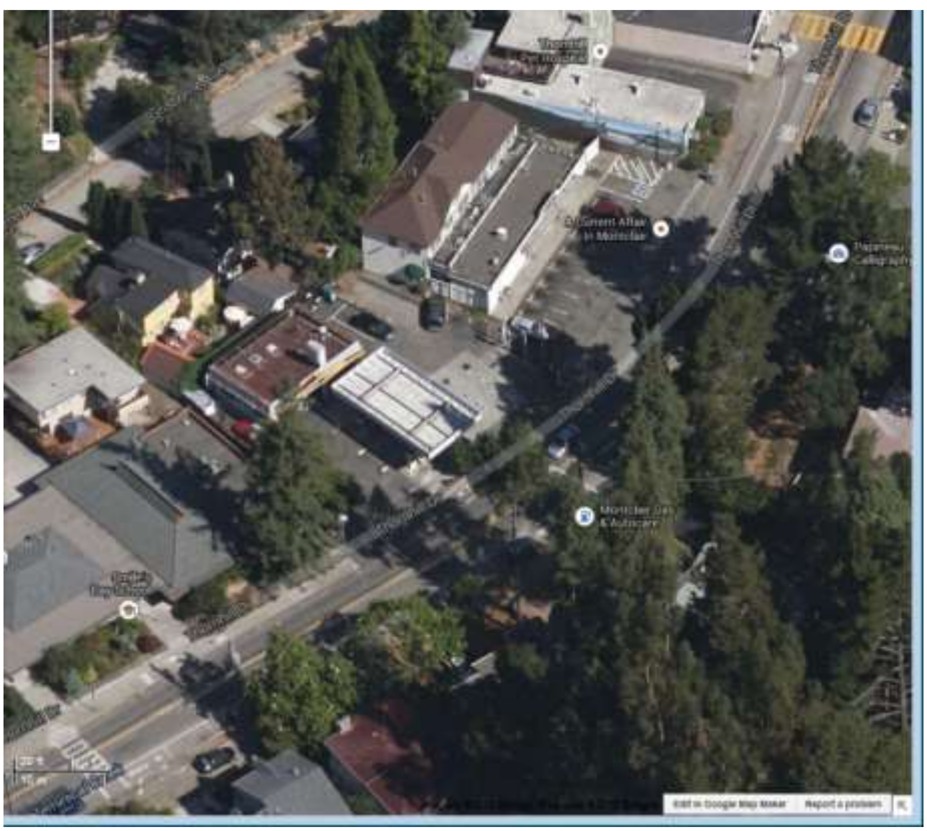


Oakland #6

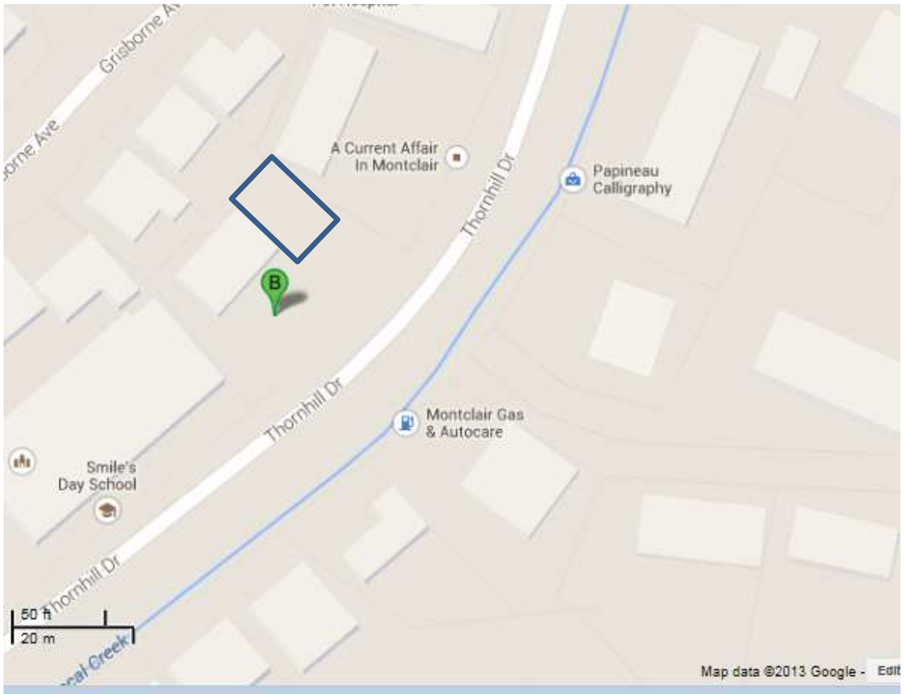
Oakland #6



Oakland #7

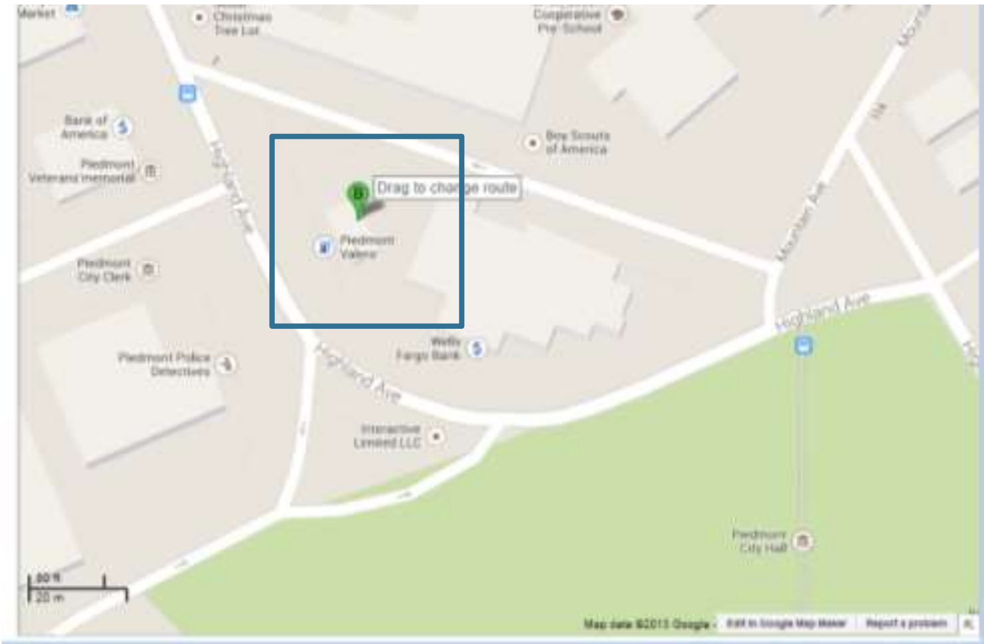


Oakland #7

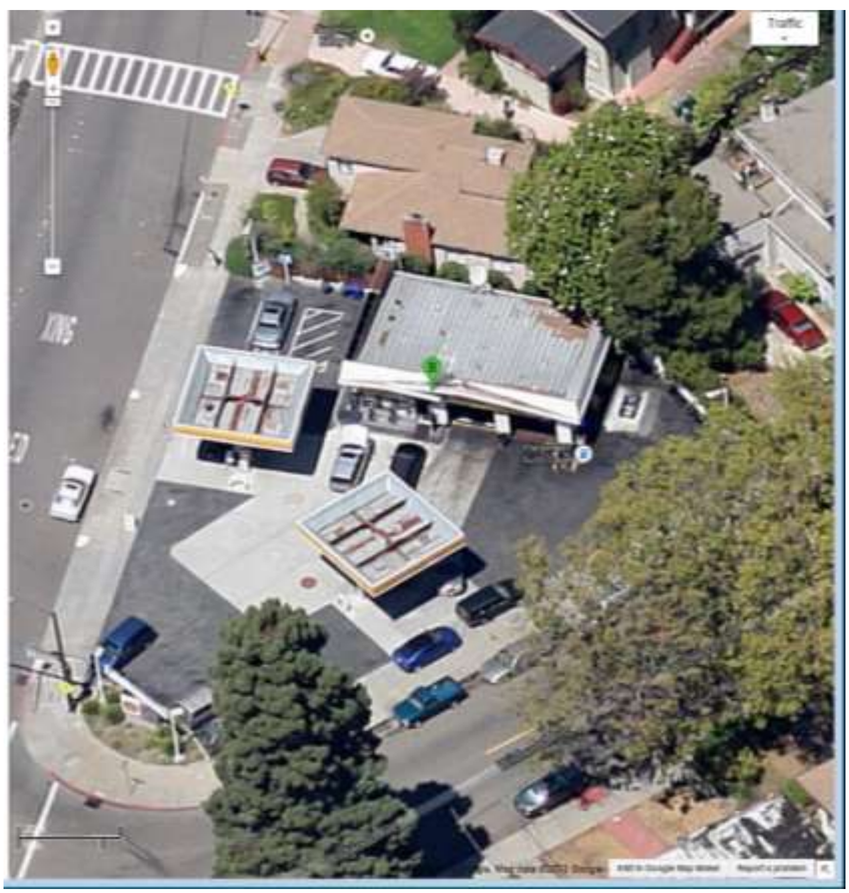


Oakland #8

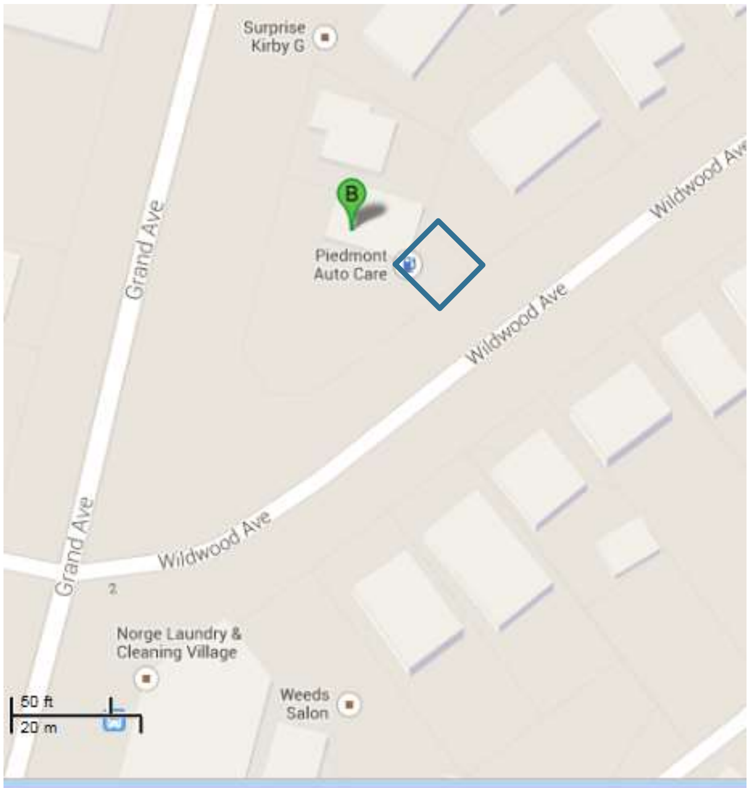
Oakland #8



Oakland #9

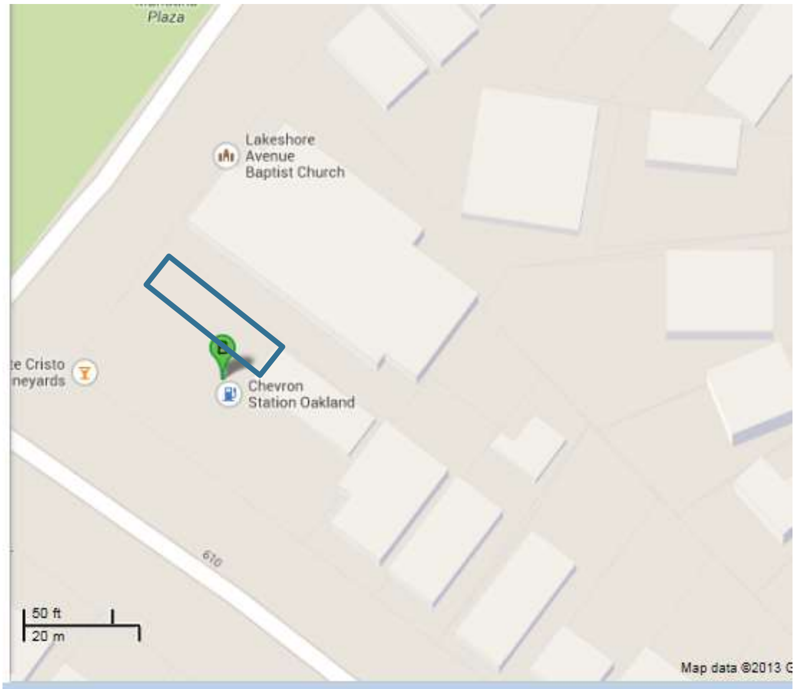


Oakland #9

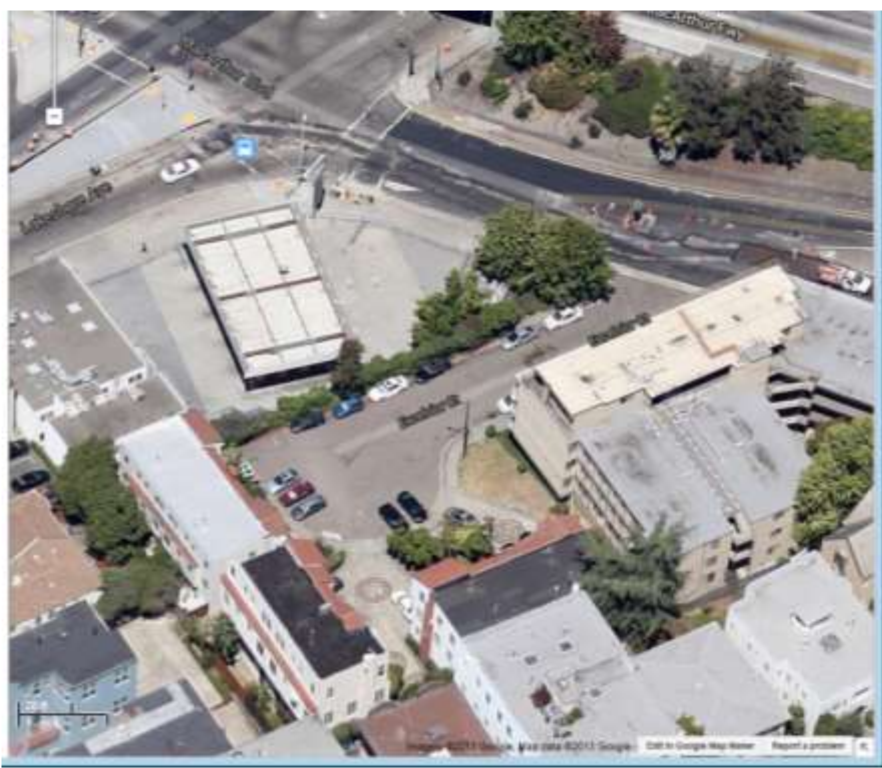


Oakland #10

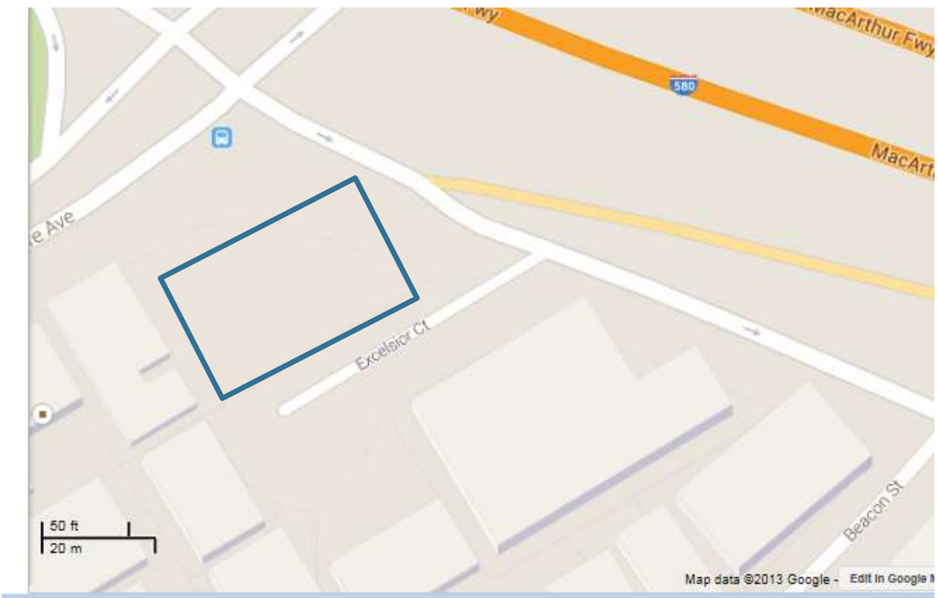
Oakland #10



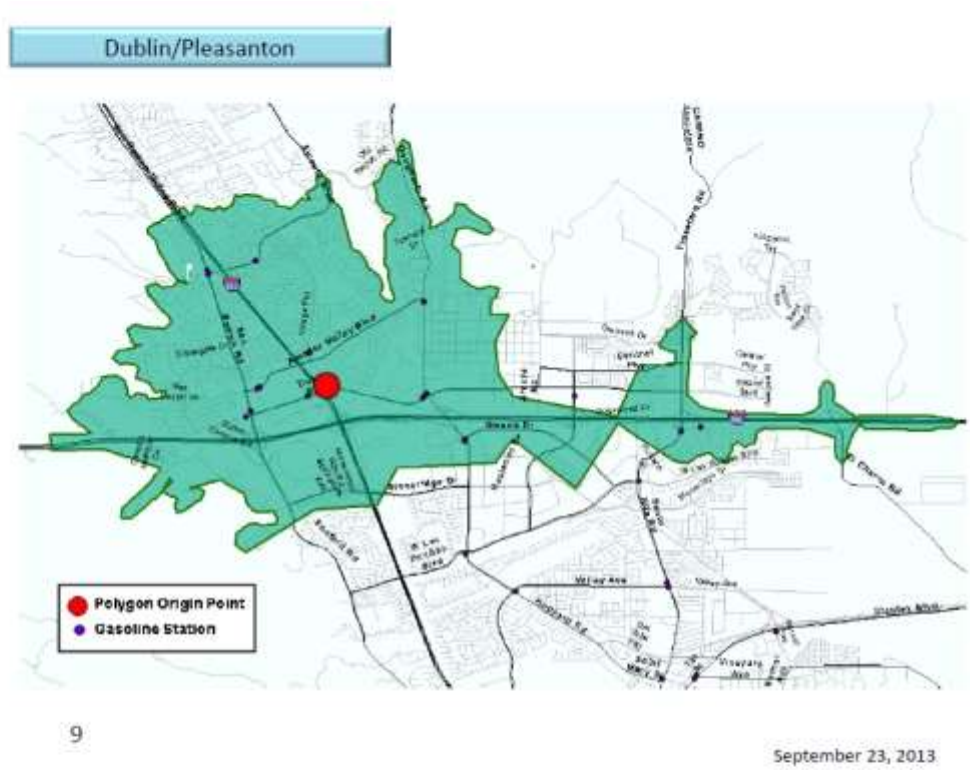
Oakland #11



Oakland #11

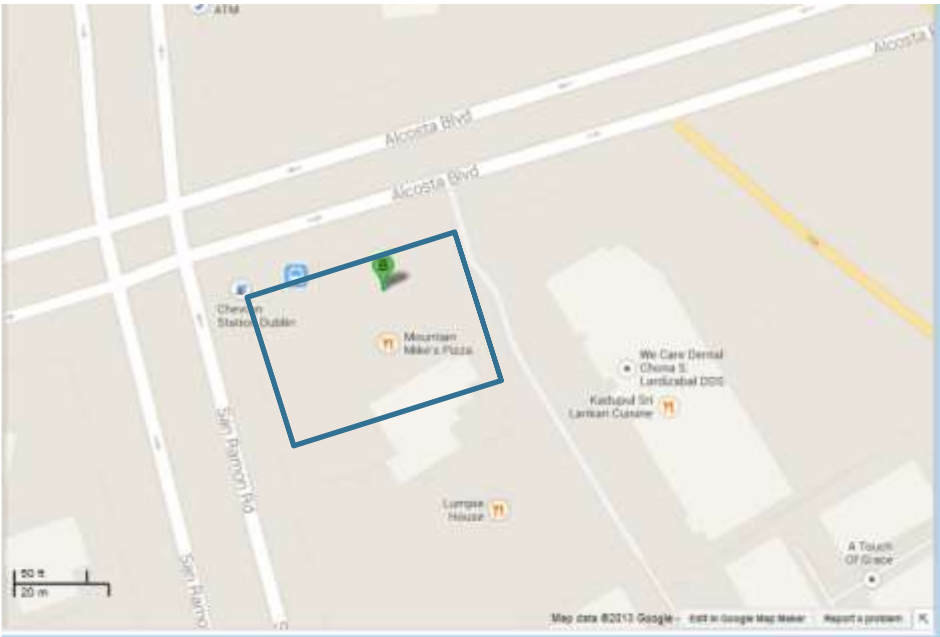

MacArthur Fwy
580
MacArt
e Ave
Excelsior Ct
Beacon St
50 ft
20 m
Map data ©2013 Google -
Edit in Google

SEC Secondary Area
Dublin (15 stations)



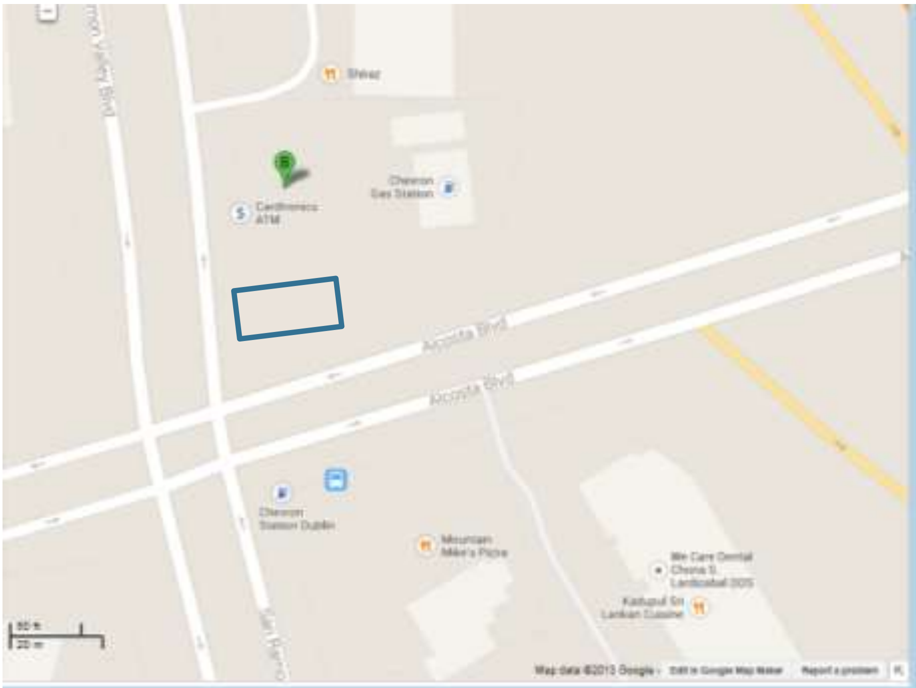
Dublin #1

Dublin #1



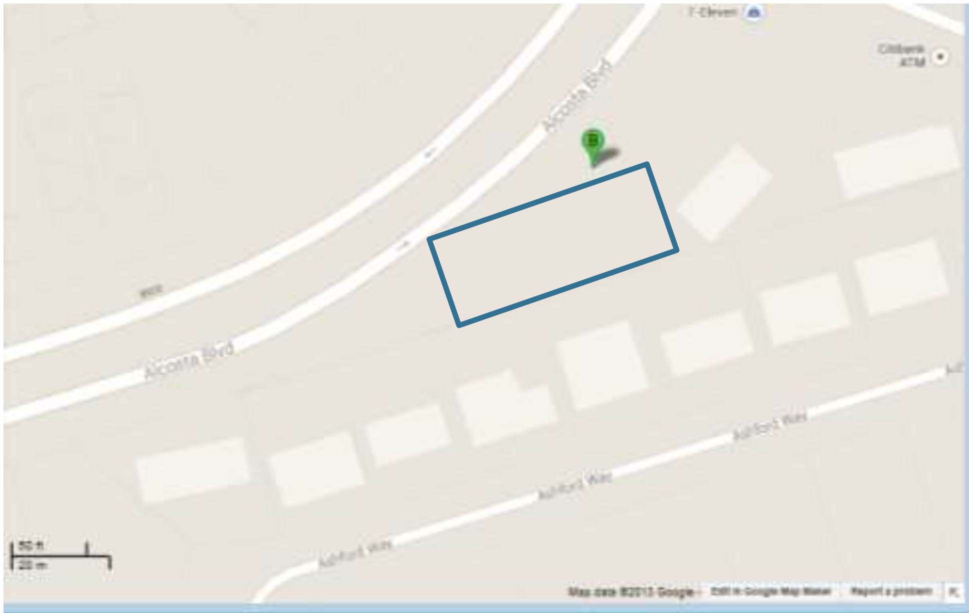
Dublin #2

Dublin #2



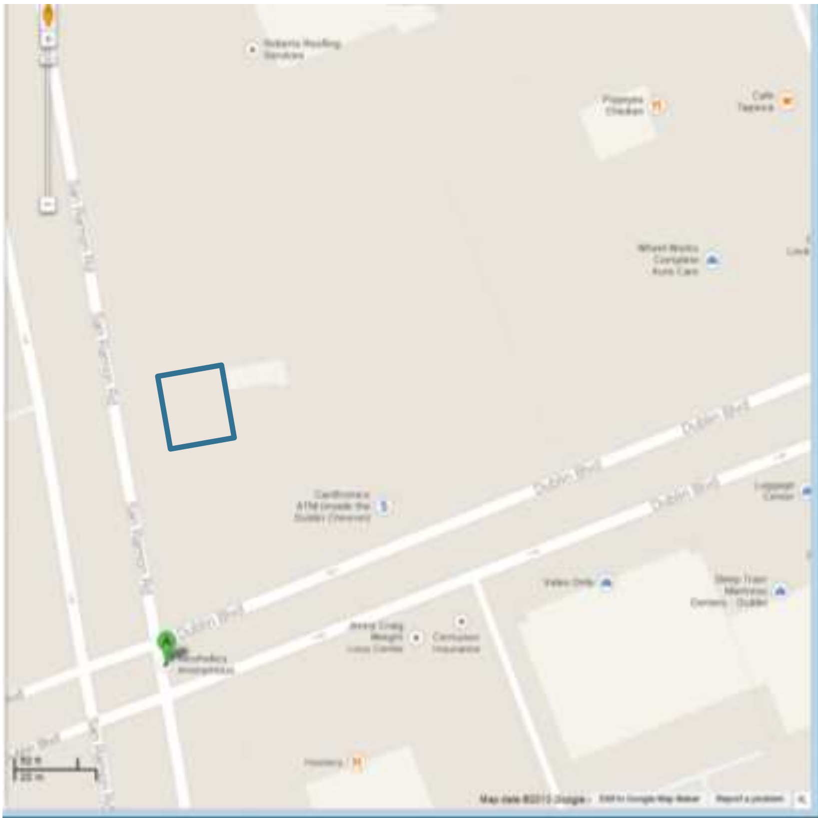
Dublin #3

Dublin #3

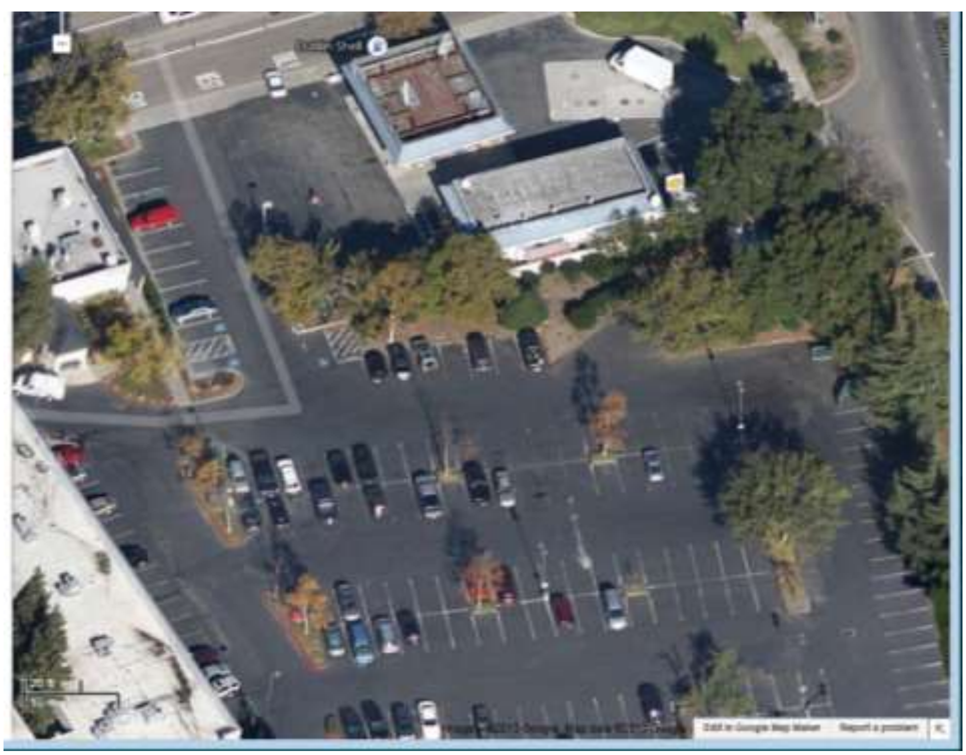


Dublin #6

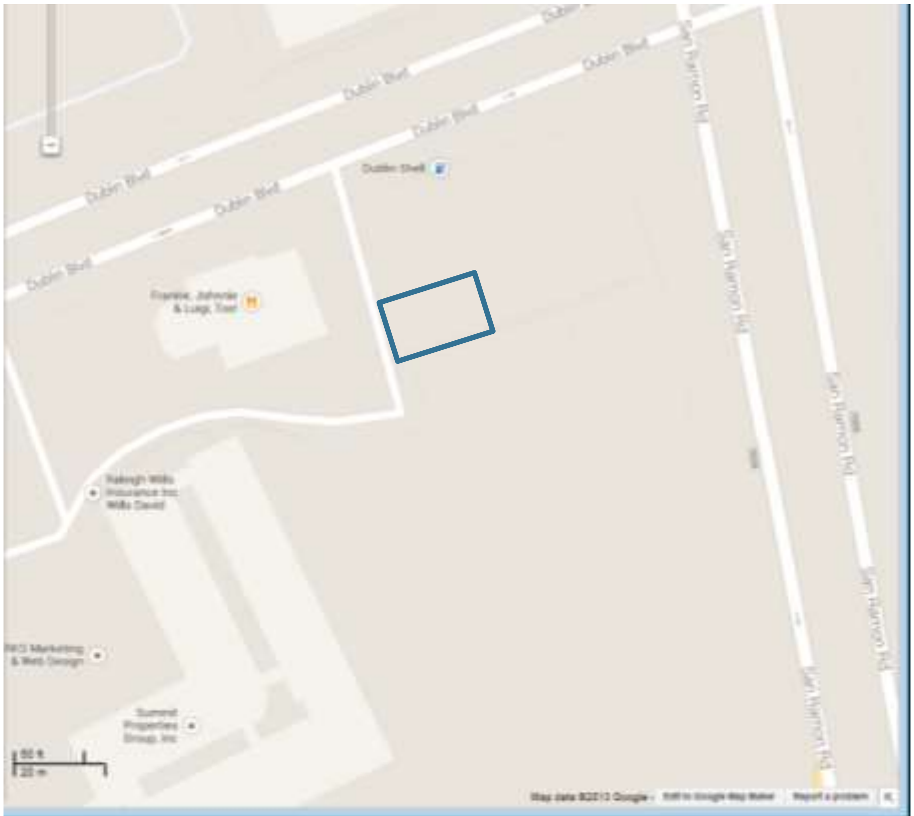
Dublin #6



Dublin #7



Dublin #7



Dublin Blvd
San Ramon Rd
Dublin Shell
Summit Properties Group, Inc

Distribution

1	MS0899	Technical Library	9536 (electronic copy)

Sandia National Laboratories