Bachelor's Degree on Industrial Engineering

CAPSTONE PROJECT

Location Model of EV charging stations in the city of Madrid

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MODELO DE UBICACIÓN DE PUNTOS DE CARGA PARA COCHES ELÉCTRICOS EN MADRID

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ABSTRACTO

El objetivo de este estudio es diseñar un modelo de localización para el desarrollo de futuras estaciones de carga rápida (50 kW y superiores) en la ciudad de Madrid utilizando técnicas de optimización. El modelo incluye las estaciones ya disponibles, así como el flujo de tráfico y la geografía de Madrid obteniendo resultados diferentes ya que las restricciones del modelo varían.

Palabras clave: EV, Charging, Madrid

1. Introducción

Nuevas medidas de transporte, el cambio climático, el auge del mercado de vehículos eléctricos (EV) y las nuevas tecnologías promueven la inversión y desarrollo de los vehículos eléctricos para los próximos años. Algunos de los mayores actores son los fabricantes de automóviles como Daimler o Volkswagen que planean una inversión multimillonaria en vehículos eléctricos, así como empresas privadas como Endesa, Iberdrola o Repsol que tienen grandes planes para la infraestructura de estaciones de carga[LIEN19] [PATIÑO18].

2. Definición del Proyecto

El propósito del proyecto es definir un modelo de ubicación óptima para estaciones de carga rápida. Existen diferentes tipos de estaciones de carga: estaciones domésticas que tienen una capacidad de potencia de 3,7 kW a 7,4 kW (Tipo 1), las estaciones de carga públicas comunes que tienen una capacidad de potencia de 3,7 kW hasta 43 kW (Tipo 2) y, finalmente, los cargadores rápidos, súper rápidos y ultra rápidos de corriente continua que proporcionan 50 kW, 150 kW y 350 kW (DCFC) ubicados en la vía pública. Este tipo de estaciones de carga de 50kW o mayor será el foco del proyecto[CAMCO20].

Además, se pueden usar diferentes tipos de conectores y modos de operación que implican una capacidad de alimentación diferente y diferente conectividad. Los conectores más comunes son tipo 2 MENNEKES y CCS para una carga rápida. Dependiendo de la estación de carga, también hay diferentes modos de carga: el modo 1 no proporciona comunicación entre el vehículo y la estación de carga, el modo 2 no proporciona comunicación ni, pero incluye una pequeña protección para garantizar la entrega de energía adecuada, el modo 3 proporciona cierta conectividad y establece una imitación de potencia de 43 kW, finalmente el modo 4 proporciona una conectividad completa entre el vehículo y la estación de carga con un límite de potencia de 350 kW y sólo está disponible en ubicaciones públicas[CAMMO20].

En Madrid las estaciones de carga están presentes en varios tipos de ubicaciones, aproximadamente: 25% están en la vía pública, 40% en aparcamiento público subterráneo, 10% en centros comerciales, 15% de aparcamiento público de superficie, 10% en hoteles, y 5% en concesionarios de automóviles y talleres de reparación de automóviles.(Fuente DGT).

Para localizar las futuras estaciones de carga, en primer lugar, la ciudad se debe proyectar en una cuadrícula formada por distintos nodos donde cada nodo de la cuadrícula represente una posible ubicación disponible y en este caso particular asignando cada nodo a uno de los barrios de Madrid. Con un total de 131 barrios dentro de los 21 distritos que tiene Madrid, la red propuesta tiene un equilibrio razonable entre la precisión de la ubicación y las iteraciones que el modelo debe realizar. Una descripción más detallada de los barrios con el nombre, número, ubicación relativa en el distrito y ubicación en la ciudad se presenta en el Anexo B. En los modelos 2, 3 y 4 también se incluyen las estaciones de carga rápida disponibles por el ayuntamiento de Madrid con 38 estaciones de carga rápida con un total de 45 conectores DCFC.[MAD20].

Según el informe del Departamento de Energía de los Estados Unidos sobre los costes asociados con los equipos de suministro de vehículos eléctricos no residenciales (2015)[USDOE15], los costes asociados con el desarrollo y operación de una estación de carga incluyen: costes de hardware unitario, costos de instalación, costes de operación y mantenimiento, factores de coste adicionales y costes públicos. El coste de la unidad de puerto único oscila entre 300$ y 1500$ para el Tipo 1, 400$ a 6,500$ para El Tipo 2 y $10,000 a $40,000 para el tipo DCFC de carga rápida. El coste promedio de instalación de un DCFC es de alrededor de 21,000$.

La demanda se calculó utilizando el tráfico entrante a la ciudad, así como el número actual de vehículos dentro de la ciudad. Utilizando la información de la DGT sólo el 0,2% del número de vehículos en España son eléctricos, donde el 82% de ellos son turismos y el 18% restante está formado por motocicletas y furgonetas. El tráfico entrante a la ciudad se obtuvo con las 5 carreteras principales que entran en la ciudad de Madrid distribuidas en el lado noreste, lado noroeste, lado oeste, lado sur y lado este. Cada sección está asociada con diferentes barrios dependiendo de su ubicación geográfica. Finalmente utilizando la Ley de Pareto, se supuso que sólo un 20% de ese tráfico potencial de automóviles eléctricos se cargaría en las estaciones de carga y se estimó que el 30% de ellos usarían estaciones de carga DCFC.

3. Descripción del modelo/sistema/herramienta

Cuatro modelos diferentes fueron diseñados teniendo en cuenta diferentes características, distancias críticas, demanda y regulaciones. Problemas similares incluyen la ubicación de almacenes logísticos[SYSOI13] o problemas de ubicación de la instalación logística para búsqueda de máxima área abarcada con drones de alcance limitado[CHAUH19].

Se utilizaron varios programas para desarrollar los modelos: Excel para la recopilación y el filtrado de datos. MATLAB para cálculos y el diseño del modelo de optimización y PowerPoint y Word para gráficos y diseños de tablas. Otros programas más adecuados para técnicas de optimización como Xpress tienen una limitación de licencia académica que ha forzado el desarrollo del modelo por completo en MATLAB. Otro posible programa es Gurobi, sin embargo, una interfaz poco intuitiva hizo que la comprensión del programa fuera lenta y compleja y MATLAB fue seleccionada como la elección final. Para el diseño de mapa MyMaps de Google Maps se utilizó ya que incluía características útiles para presentar mapas editados de manera clara.

Formulación y breve objetivo de los modelos:

Modelo 1: máxima área abarcada con dos distancias críticas diferentes de 1Km y 2Km.

Minimizar $\sum_i X_i$

Sujeto a: $\sum_i a_{ij} X_i \geq 1 \quad \forall \ j \in \mathbf{N}$

$X_i = 0{,}1 \quad \forall \ i \in \mathbf{N}$

Dónde

$$Xi \begin{cases} 1 \ si \ una \ estación \ EV \ se \ debe \ construir \ en \ el \ nodo \ i \\ 0 \ de \ lo \ caontrario \end{cases} \forall \ i$$

$$a_{ij} \begin{cases} 1 \ si \ el \ nodo \ i \ se \ encuentra \ dentro \ de \ la \ distancia \ crítica \ D \ del \ nodo \ j \\ 0 \ de \ lo \ contrario \end{cases}$$

$N = \{1,2,3 \ldots 131\} \ (nodos)$

Modelo 2: máxima área abarcada con dos distancias críticas diferentes de 1Km y 2Km incluyendo las DCFC disponibles.

Minimizar $\sum_i X_i$

Sujeto a: $\sum_i a_{ij}(X_i + K_m) \geq 1 \quad \forall \ j \in \mathbf{N} \ \forall \ m \in \mathbf{M}$

$X_i = 0{,}1 \quad \forall \ i \in \mathbf{N}$

Dónde

$$Xi \begin{cases} 1 \ si \ una \ estación \ EV \ se \ debe \ construir \ en \ el \ nodo \ i \\ 0 \ de \ lo \ contrario \end{cases} \forall \ i$$

$$a_{ij} \begin{cases} 1 \ si \ el \ nodo \ i \ se \ encuentra \ dentro \ de \ la \ distancia \ crítica \ D \ del \ nodo \ j \\ 0 \ de \ lo \ contrario \end{cases}$$

$K_m = número \ de \ conectores \ en \ la \ estación \ M$(parámetro)

$M = \{1,2,3, \ldots 38\}$(estaciones de carga ya disponibles)

Modelo 3: máxima área abarcada con una distancia crítica de 1,5 Km, incluidos las DCFC disponibles, así como la demanda asociada a cada nodo limitado con dos conectores por nueva ubicación.

Minimizar $\sum_i X_i$

Sujeto a: $\sum_i a_{ij}(X_i + K_m) \geq 1 \quad \forall \ j \in \mathbf{N} \ \forall \ m \in \mathbf{M}$

$\sum_i a_{ij} Y_i \geq R_i \quad \forall \ j \in \mathbf{N}$

$\boldsymbol{Y_i} \leq \mathbf{2} * \boldsymbol{X_i} \ \forall \ i \in \mathbf{N}$

$\sum_i Y_i \geq \sum_i R_i \quad \forall \ j \in \mathbf{N}$

$X_i = 0{,}1 \quad \forall \ i \in \mathbf{N}$

$Yi = 0{,}1{,}2 \ \forall \ i$

Dónde

$$Xi \begin{cases} 1 \ si \ una \ estación \ EV \ se \ debe \ construir \ en \ el \ nodo \ i \\ 0 \ de \ lo \ contrario \end{cases} \forall \ i$$

$Yi = número \ de \ conectores \ en \ la \ estación \ i \ \forall \ i$

$Ri = número \ de \ vehículos \ que \ solicitan \ carga \ en \ el \ nodo \ i \ \forall \ i$

$$a_{ij}\begin{cases}1\ si\ el\ nodo\ i\ se\ encuentra\ dentro\ de\ la\ distancia\ crítica\ D\ del\ nodo\ j\\ 0\ de\ lo\ contrario\end{cases}$$

$K_m = número\ de\ conectores\ en\ la\ estación\ M$(parámetro)

$M = \{1,2,3,\ldots 38\}$(estaciones de carga ya disponibles)

$N = \{1,2,3,\ldots 131\}\ (nodos)$

Modelo 4: máxima área abarcada con una distancia crítica de 1,5 Km, incluyendo las DCFC disponibles, así como la demanda asociada a cada nodo y proporcionando una asociación de costos a tres áreas diferentes limitadas con dos conectores por nueva ubicación.

Minimizar $\sum_l X_l + 2 * \sum_g X_g + 3 * \sum_f X_f \quad \forall\ l \in \mathbf{L}\ \forall\ g \in \mathbf{G}\ \forall\ f \in \mathbf{F}$

Sujeto a: $\sum_i a_{ij}(X_i + K_m) \geq 1 \quad \forall\ j \in \mathbf{N}\ \forall\ m \in \mathbf{M}$

$\sum_i a_{ij} Y_i \geq R_i \quad \forall\ j \in \mathbf{N}$

$\boldsymbol{Y_i \leq 2 * X_i} \ \forall\ i \in \mathbf{N}$

$\sum_i Y_i \geq \sum_i R_i \quad \forall\ j \in \mathbf{N}$

$X_i = 0{,}1 \quad \forall\ i \in \mathbf{N}$

$Yi = 0{,}1{,}2\ \forall\ i$

Dónde

$$Xi\begin{cases}1\ si\ una\ estación\ EV\ se\ debe\ construir\ en\ el\ nodo\ i\\ 0\ de\ lo\ contrario\end{cases}\ \forall\ i$$

$Yi = número\ de\ conectores\ en\ la\ estación\ i\ \forall\ i$

$Ri = número\ de\ vehículos\ que\ solicitan\ carga\ en\ el\ nodo\ i\ \forall\ i$

$$a_{ij}\begin{cases}1\ si\ el\ nodo\ i\ se\ encuentra\ dentro\ de\ la\ distancia\ crítica\ D\ del\ nodo\ j\\ 0\ de\ lo\ contrario\end{cases}$$

$K_m = número\ de\ conectores\ en\ la\ estación\ M$(parámetro)

$M = \{1,2,3,\ldots 38\}$(estaciones de carga ya disponibles)

$N = \{1,2,3,\ldots 131\}\ (nodos)$

L-1,2,3,4,5,6o (nodos centrales de Madrid)

G-7,8,9... 42,43o (nodos M-30)

F-44,45,130,131o (Nodos restantes)

4. Resultados

Para cada modelo y submodelo se diseñó un mapa utilizando MyMaps para presentar el resultado del modelo de optimización. Un mapa de modelo se presenta como la figura siguiente donde los marcadores de color azul claro representan las DCFC ya disponibles, mientras que los otros marcadores de color representan los diferentes distritos.

Abstracto Figura 1Modelo 2.1

Los resultados finales se presentan en la siguiente tabla:

Modelo	Distancia crítica	Nuevas estaciones de carga
1.1	1Km	83
1.2	2Km	31
2.1	2Km	21
2.2	1Km	68
3	1.5Km	53
4	1.5Km	54

Abstracto Tabla. 1Resultados finales

5. Conclusiones

El proyecto ha desarrollado diferentes modelos con distintas restricciones que podrían adaptarse a de acuerdo con las prioridades a la hora de construir nuevas estaciones de carga para el futuro. El último modelo refleja el mejor comportamiento de la ciudad ya que considera la ubicación del tráfico, el número de coches por barrio para estimar la demanda, así como teniendo en cuenta las nuevas normas de tráfico que se han establecido con la zona Madrid Central y la zona M30. Estos modelos pueden ayudar a empresas privadas como Repsol, Iberdrola, GIC, EMT o el Ayuntamiento a comprender la mejor ubicación para futuras estaciones de carga que se necesitarán en el futuro para continuar la transición a una ciudad más verde donde el vehículo eléctrico tenga un papel principal en el sistema de transporte y movilidad de Madrid.

LOCATION MODEL OF EV CHARGING STATIONS IN THE CITY OF MADRID

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ABSTRACT

The purpose of this study is to design a location model for the development of future fast charging stations (50 kW and above) in the city of Madrid using optimization techniques. The model includes the stations already available as well as traffic flow and Madrid's geography obtaining different results as model constraints vary.

Keywords: EV, Charging, Madrid

1. Introduction

Government policies, climate change, standing out in the electric vehicle (EV) market and new technologies aid private companies to make great investments for the upcoming years. Some of the biggest stakeholders are automakers such as Daimler or Volkswagen that plan a multimillion investment on EV's as well as private companies such as Endesa, Iberdrola or Repsol that have great plans and pushing forward for the EV infrastructure[LIEN19] [PATIÑO18].

2. Project definition

The purpose of the project is to define an optimal location model for fast charging stations. There are different type of charging stations: home chargers which have a power capacity of 3.7 kW to 7.4 kW (Type 1), the common public charging stations which have a power capacity of 3.7 kW up to 43 kW (Type 2)and finally, the direct current fast, superfast and ultrafast chargers that provide 50 kW, 150 kW and 350 kW (DCFC) correspondingly located only on public roads. These type of charging stations will be the focus of the project[CAMCO20].

There are also different types of connectors and modes of operation that involve different power capacity and different connectivity. The most common connectors are Type 2 MENNEKES and CCS for fast charging. Depending on the charging station, there are as well different modes of charging: Mode 1 provides no communication between the vehicle and the charging station, Mode 2 doesn't provide communication neither but includes a small protection to ensure the proper power delivery, Mode 3 provides some connectivity and establishes a power imitation of 43 kW, finally Mode 4 provides complete connectivity between vehicle and charging station with a power limit of 350 kW and is only available on public locations[CAMMO20].

There are different types of locations for the charging stations as well. In Madrid approximately: 25% are on street , 40% on underground public parking, 10% in shopping centers, 15% surface public parking, 10% on hotels, and 5% on car dealerships and car repair shops.(Source DGT).

To locate the future charging stations firstly the city must be mapped into a grid so that each node on the grid represents a possible available location. With a total number of

131 neighborhoods across the 21 districts Madrid's grid would have a reasonable compromise between location effectiveness and computing power. A more detailed description of the neighborhoods with the name, number, relative location on the district and location on the city is presented on Annex B. On models 2 to 4 the available charging stations are also included which presented by Madrid's city council data there are 38 fast charging stations with a total of 45 DCFC connectors.[MAD20].

According to the U.S.Department of Energy report on Costs Associated with non-residential electric vehicle supply equipment (2015) [USDOE15],the costs associated with the development and operation of a charging station include: unit hardware costs, installation costs, operation and maintenance costs, additional cost factors and public costs. The single port unit cost ranges from 300$ to 1500$ for Type 1, 400$ to 6,500$ for Type 2 and $10,000 to $40,000 for fast charging DCFC type. The average installation cost for a DCFC is around 21,000$.

The demand was calculated using the incoming traffic to the city as well as the present number of vehicles inside the city. Using DGT information only 0.2% of the number of vehicles in Spain are electric where 82% of those are cars and the remaining 18% is formed by motorcycles and vans. The incoming traffic to the city was obtained with the 5 main roads that enter the city of Madrid distributed on the North East side, North West side, West side, South side, and East side. Each section is associated with different neighborhoods depending on their geographic location. Finally using Pareto's Law, it was assumed that only a 20% of that potential electric car traffic would charge on charging stations and it was estimated that 30% of those would arrive to DCFC.

3. Description of the model/system/tool

Four different models were designed considering different characteristics, critical distances, demand, and regulations. Similar problems include the location of logistic warehouses [SYSOI13] or the maximum coverage capacitated facility location problems with range constrained drones [CHAUH19].

Multiple programs were utilized to develop the models: Excel for data gathering and filtering. MATLAB for calculations and the optimization model design and PowerPoint and Word for charts and table designs. Other programs more suited for optimization techniques such as Xpress have an academic license limitation than has forced the complete development of the model on MATLAB. Other possible program was Gurobi, however the unintuitive interface made the understanding of the program slow and complex and MATLAB was selected as the final choice. For the map design MyMaps by Google Maps was used because it included useful features to present clean edited maps.

Formulation and brief objective of the models:

Model 1: Maximum set covering problem with two different critical distances of 1Km and 2Km.

Minimize $\sum_i X_i$

Subject to: $\sum_i a_{ij} X_i \geq 1 \quad \forall \; j \in \mathbf{N}$

$X_i = 0{,}1 \quad \forall \; i \in \mathbf{N}$

Where

$$Xi \begin{cases} 1\ if\ an\ EV\ station\ is\ located\ on\ node\ i \\ 0\ otherwise \end{cases} \forall\ \ i$$

$$a_{ij} \begin{cases} 1\ if\ node\ i\ is\ under\ the\ critical\ distance\ D\ from\ node\ j \\ 0\ otherwise \end{cases}$$

$N = \{1,2,3\ldots131\}$ $(nodes)$

Model 2: Maximum set covering problem with two different critical distances of 1Km and 2Km including the available DCFC.

Minimize $\sum_i X_i$

Subject to: $\sum_i a_{ij}(X_i + K_m) \geq 1 \quad \forall\ \ j \in \mathbf{N}\ \forall\ \ m \in \mathbf{M}$

$X_i = 0{,}1 \quad \forall\ i \in \mathbf{N}$

Where

$$Xi \begin{cases} 1\ if\ an\ EV\ station\ is\ located\ on\ node\ i \\ 0\ otherwise \end{cases} \forall\ \ i$$

$$a_{ij} \begin{cases} 1\ if\ node\ i\ is\ under\ the\ critical\ distance\ D\ from\ node\ j \\ 0\ otherwise \end{cases}$$

$K_m = number\ of\ connectors\ at\ station\ M$ (parameter)

$M = \{1,2,3,\ldots38\}$ (charging stations already available)

Model 3: Maximum set covering problem with a critical distance of 1.5 Km including the available DCFC as well as the demand associated to each node limited with two connectors per new location.

Minimize $\sum_i X_i$

Subject to: $\sum_i a_{ij}(X_i + K_m) \geq 1 \quad \forall\ \ j \in \mathbf{N}\ \forall\ \ m \in \mathbf{M}$

$\sum_i a_{ij}Y_i \geq R_i \quad \forall\ \ j \in \mathbf{N}$

$\boldsymbol{Y_i} \leq \mathbf{2} * \boldsymbol{X_i}\ \forall\ i \in \mathbf{N}$

$\sum_i Y_i \geq \sum_i R_i \quad \forall\ \ j \in \mathbf{N}$

$X_i = 0{,}1 \quad \forall\ i \in \mathbf{N}$

$Yi = 0{,}1{,}2\ \forall\ \ i$

Where

$$Xi \begin{cases} 1\ if\ an\ EV\ station\ is\ located\ on\ node\ i \\ 0\ otherwise \end{cases} \forall\ \ i$$

$Yi = number\ of\ connectors\ per\ station\ i\ \forall\ \ i$

$Ri = number\ of\ vehicles\ that\ demand\ charge\ at\ node\ i\ \forall\ \ i$

$$a_{ij} \begin{cases} 1\ if\ node\ i\ is\ under\ the\ critical\ distance\ D\ from\ node\ j \\ 0\ otherwise \end{cases}$$

$K_m = number\ of\ connectors\ at\ station\ M$ (parameter)

$M = \{1,2,3,\ldots38\}$ (charging stations already available)

$N = \{1,2,3,\ldots131\}$ $(nodes)$

Model 4: Maximum set covering problem with a critical distance of 1.5 Km including the available DCFC as well as the demand associated to each node and providing a cost association to areas limited with two connectors per new location.

Minimize $\sum_l X_l + 2 * \sum_g X_g + 3 * \sum_f X_f \quad \forall\ \ l \in \mathbf{L}\ \forall\ \ g \in \mathbf{G}\ \forall\ \ f \in \mathbf{F}$

Subject to: $\sum_i a_{ij}(X_i + K_m) \geq 1 \quad \forall\ \ j \in \mathbf{N}\ \forall\ \ m \in \mathbf{M}$

$$\sum_i a_{ij} Y_i \geq R_i \quad \forall \ j \in \mathbf{N}$$
$$\boldsymbol{Y_i \leq 2 * X_i} \ \forall \ i \in \mathbf{N}$$
$$\sum_i Y_i \geq \sum_i R_i \quad \forall \ j \in \mathbf{N}$$
$$X_i = 0{,}1 \quad \forall \ i \in \mathbf{N}$$
$$Yi = 0{,}1{,}2 \ \forall \ i$$

Where

$$Xi \begin{cases} 1 \ if \ an \ EV \ station \ is \ located \ on \ node \ i \\ 0 \ otherwise \end{cases} \forall \ i$$

$Yi = number \ of \ connectors \ per \ station \ i \ \forall \ i$

$Ri = number \ of \ vehicles \ that \ demand \ charge \ at \ node \ i \ \forall \ i$

$$a_{ij} \begin{cases} 1 \ if \ node \ i \ is \ under \ the \ critical \ distance \ D \ from \ node \ j \\ 0 \ otherwise \end{cases}$$

$K_m = number \ of \ connectors \ at \ station \ M$ (parameter)

$M = \{1,2,3,\ldots 38\}$ (charging stations already available)

$N = \{1,2,3,\ldots 131\} \ (nodes)$

L={1,2,3,4,5,6}(Madrid central nodes)

G={7,8,9…42,43}(M-30 nodes)

F={44,45,130,131}(Remaining nodes)

4. Results

For every model and sub model a map was designed using MyMaps to present the result of the optimization model. A model map is presented as the figure below where the light blue markers represent the DCFC already available while the other color markers represent the different districts.

Abstract Figure 2Model 2.1

The results are presented on the table below:

Model	Critical distance	New Charging Stations
1.1	1Km	83

1.2	2Km	31
2.1	2Km	21
2.2	1Km	68
3	1.5Km	53
4	1.5Km	54

Abstract Table. 2Final Results

5. Conclusions

The project has developed different models according to different restrictions that could suit different priorities when building new charging stations for the future. The last model reflects the best behavior of the city as it considers the traffic location, the number of cars per neighborhood to estimate the demand as well as considering the new traffic regulations that has been stablished with Madrid Central area and M30 area. These models can help private companies such as Repsol, Iberdrola, GIC, EMT or the city council understand the best location for future charging stations as they are going to be needed in the future to continue the transition to a greener city where the electric vehicle will be a key factor in the transportation system.

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Abbreviations

Abbreviation	Description
EV	Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
BEV	Battery Electric Vehicle
EU	European Union
AC	Alternating Current
DC	Direct Current
DCFC	Direct Current Fast Charger
SAE	Society of Automotive Engineers
CCS	Combined Charging System
SDG	Sustainable development goals
UMTX	Universal Transverse Mercator X-coordinate
UMTY	Universal Transverse Mercator Y-coordinate
DGT	*Dirección General de Tráfico,* public agency traffic regulator
O&M	Operation and Maintenance

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1. INTRODUCTION

According to a study conducted by Reuters in 2019 global automakers plan to spend at least $300 billion in electric vehicles in a five to ten-year plan. Government policies, climate change, standing out in the electric vehicle (EV) market and new technologies aid private companies to make these great investments. Companies such as Volkswagen or Daimler (two of the biggest auto-manufacturers) will have a total EV investment of 91 and 42 billion, respectively [LIEN19].

As the electric vehicle production grows charging stations will have to keep up to solve the problem of the demand of charging stations. This new charging stations will have to be placed in some locations where they are easy accessible, there is a high demand of charging stations (high density of population events, offices, new buildings on construction…), other considerable factors would be the financial capabilities and resources the government is able to make as well as having new charging stations nor to close nor to far from each other. Choosing the right location for an EV station is as important as including new charging stations, the two problems go hand by hand. The following capstone project has been divided in three chronological stages: Research stage, Development of the optimization models, and Final Report and Presentation generation. On the first section the focus was centered on the gathering of quantitative data, the previous and present legislation that rules the charging station regulation. On the second stage of the project the models were developed based on different requirements and characteristics that will be mentioned later. Moreover, about the structure of the report, the paper is divided into eight parts: a brief introduction on the first three pages of the document, followed by the technology description where detailed functions will be explained to understand the model program design, the state of the art will be explained from pages fourteen to twenty two where charging stations connectors and location comparisons are presented, pages twenty two to twenty five include the project description, the justification of the project, a broad cost analysis, the objective of the project and the methodology used to achieve those objectives, chapter five describes the model geographic distribution, the vehicles of study and the traffic and demand study on pages twenty five to thirty one, afterwards the four model designs will be presented associated with the corresponding formulation, final results and location on the map, chapter seven summarizes the conclusions found on the project and suggests future work to improve the model design. Lastly chapter 8 includes the references that the project is based on to end up with an annex section where more detailed work on sustainable development goals, districts and neighborhood information, and the incoming traffic to the city can be found.

This project will study the optimal location model of new electric vehicle fast charging stations (50 kW or above) in the city of Madrid according to four main aspects. First, maximum coverage of each station assuming a radius of 1 and 2 kilometers between stations. Second, maximum coverage of each station assuming a radius of 1 and 2 kilometers between stations including the 38 fast charging stations available in the city. The third model was designed with a 1.5 kilometer radius including previous stations and the demand that each node might have. And the fourth model presents a more fitted and complete configuration for the city by weighting more areas according to the government's legislation (Madrid Central, Car distinctives …).

An electric vehicle charging station consists of a charging doc that allows electric and plug-in hybrid electric vehicles (PHEV) to charge their batteries so the user can continue driving as it is seen on figure 1.1. The two locations where users charge their car could be separated in two categories, home charging and public charging. Most of the electric vehicle owners install a wall connection at home which provides more power for their batteries compared to the standard EU output of 220V.

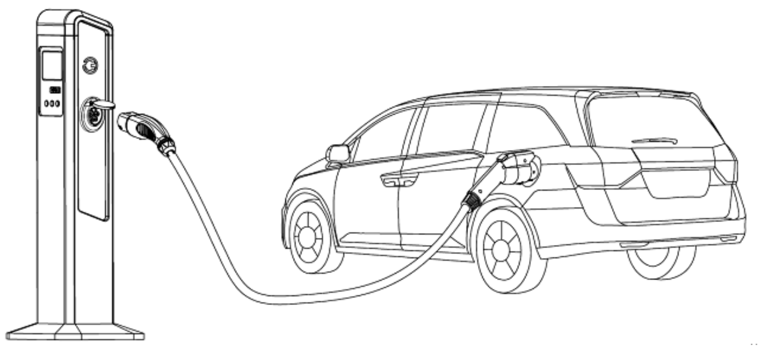


Figure 1.1 Electric vehicle connected to an EV post.[ALIB20]

Even though the drivers could use the standard EU outlet to charge their vehicle, there are two main reasons why it is not recommended. First, the charge would take too long to charge completely and second, due to safety issues because the standard outlet is not designed to withstand at its maximum capacity for long periods of time. Charging at home becomes the most convenient and cost-effective way to provide power to the car. There are also government incentives for its installation as well as promotions with car dealerships when you buy an electric vehicle. Home chargers are usually rated from 3.7 kW to 7.4 kW [MCKIN14]. There is a compromise between charging time and the incurred cost of the charging point that the user should consider fitting its car conditions. The other location to charge a vehicle would be on public networks. These stations are equipped with different connectors and modes of charging to provide more power for the user. The power capacity of this stations is commonly rated between 3.7 kW to 50 kW on the city, there are some exceptions like the Tesla's new V3 supercharger designed to reach up to 150 kW(only one station in the city of Madrid) and up to 350 kW on a few gas stations across the highways of Spain and other countries of the EU.

Although some of the charging stations are free (Tesla supercharger for tesla users), fast and rapid chargers require payment. In the city which will be our focus, the payment and access methods across the network will vary. Most networks require an app associated preregistration with apps such as electromaps, Empark and more. Credit card is also becoming a payment option on fast charging stations [RUIZ19].

2. STATE OF THE ART

According to electromaps, the second most used app after Google Maps for charging point locations, the following chart compares connectors and locations across the fourth most relevant countries in the EU.

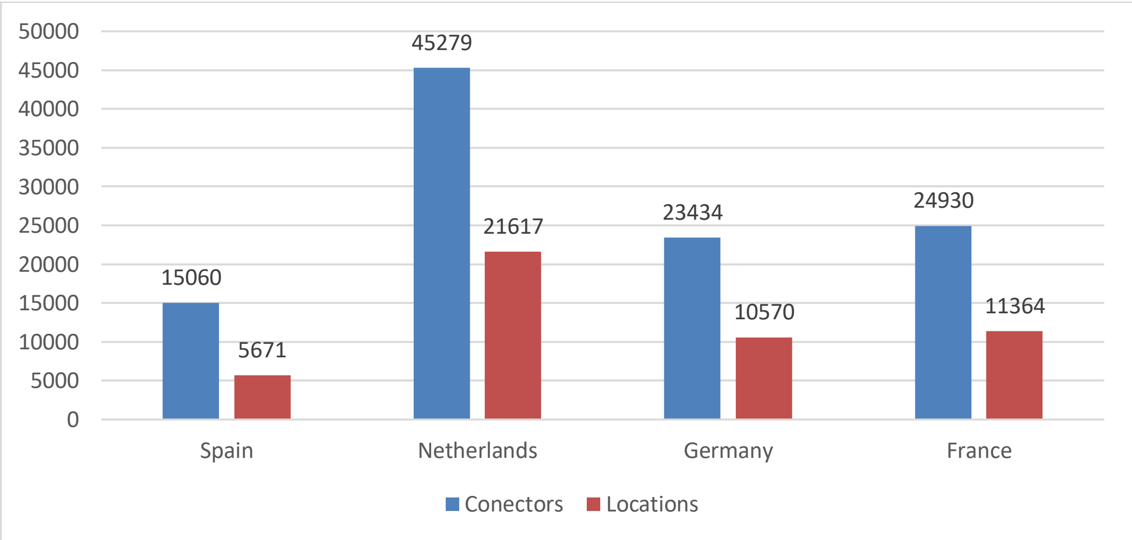


Figure 2.1 Country comparison connectors and locations [ELECTR20]

Out of the 15,060 connectors in Spain, most of them are located in Madrid with 1,824 connectors in 615 different locations and Barcelona with 2757 connectors across 777 locations.

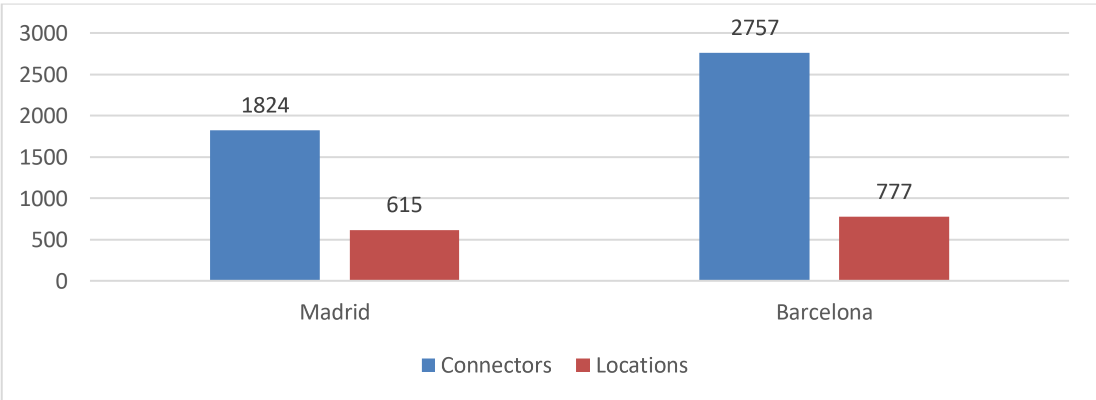


Figure 2.2 City comparison connectors and locations [ELCMA20] [ELCBA20]

2.1 TYPE OF CONNECTORS AND LOCATIONS

There are several types of connectors on the market, the differences and similarities between the connectors located in the city of Madrid are shown in table 2.1. The biggest differences vary depending on the type of charging and if it is AC or DC charging. Since there isn´t a standard yet, some countries and manufacturers use three types of charging while others only use two (Madrid's and EU's standard). According to electromaps as of 2020, Type 1(SAE J1772) has four terminals and allows between 16A and 80A providing a maximum capacity of 7,4 kW. Type 1 connectors are becoming extinct and can be found in first generation Nissan Leaf and Kia Soul amongst others. Type 2 (Mennekes), considered the standard in Europe has seven terminals and allows between single-phase 16A charge or three-phase 63A giving a maximum power of 43 kW. The CHAdeMO connector has 10 terminals and provides fast DC charging up to 200A and 50 kW. This type of connector is also becoming less used as new alternatives for fast charging such as CCS(Combined Charging System) come along. Finally, CCS is also becoming the standard for fast charging and ultra-fast charging in the EU. It has a type 2 connector providing the alternating current attached to two terminals providing DC current. This combination allows charges up to 350 kW, but it is more often used at 50 kW [CAMCO20].

Type of connector	Symbol	Number of connectors in Madrid	Standard type	AC/DC	Characteristics
TYPE 2/MENNEKES		980	Mode 1-2	AC	3 phase electricity (formal charger for the EV's in the EU)
Schuko		482	mode 1-2	AC	Single-phase 3,7 kW at maximum

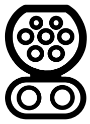
Tesla Destiny Charger		87	mode 2-3	AC	Mennekes with greater power capacity
CHAdeMO		80	Mode 3-4	AC/DC	Fast charging
CCS(Combined Charging System or 'Combo')		71	Mode 3-4	DC	Fast charging

Table 2.1 Overview of the most common connectors in Madrid [CAMCO20]

Another important consideration is the mode in which the power is provided to the car. There are four modes of operation: Mode 1 refers to the point or infrastructure that connects directly to the car and there is no communication between the EV and the charging point. The maximum current is 16A at 230V and therefore 3,7 kW of power provided(recommended for small batteries such as those in electric scooters). Very similar to Mode 1, Mode 2 has the same charging capabilities but includes a protection device and a small degree of connectivity between the car and the point to verify the connection. Ideal for small battery electric cars and plug-in hybrids or electric scooters. Mode 3 is becoming the standard amongst all locations from home to hotels and public parking. Mode 3 is available in charging points known as the Wallbox and the main market is BEV or plug-in hybrids. It is incorporated with high connectivity systems between the car and the infrastructure to monitor the charge and secure both the Wallbox and the vehicle. Mode 3 average use intensity single phase 32 A and 7,4 kW, although it can reach with three-phase up to 63A and 43 kW. To have Mode 3 both type1(SAE J1772) and type 2(Mennekes) connectors can be used. Lastly, Mode 4 delivers up to 350kW with an average use of at least 50 kW. This mode can charge the average electric vehicle to 80% in approximately 30 minutes. The availability of Mode 4 requires from CHAdeMO or CCS connectors, the only connectors that can provide such power when plugged. Mode 4 is only accessible on public locations and when selecting this mode there is total communication between the vehicle and the charging station [CAMMO20].

There are different types of locations for the charging stations as well. In Madrid approximately: 25% are on street , 40% on underground public parking, 10% in shopping centers, 15% surface public parking, 10% on hotels, and 5% on car dealerships and car repair shops.

- On the street:

The standard on street connection usually provides between one and three different type of connectors (TYPE 2 11.00 kW,CCS2 50.00 kW, CHAdeMO 50.00 kW) and only one available parking spot. For example, those in Genova 26 Street figure 3.3 and Manuel de Silvela 16 Street figure 3.4.

Figure 2.3 Génova 26 [Google Maps]

Figure 2.4 Manuel de Silvela 16 [Google Maps]

- Motorcycle only charging stations.

On the one hand, these charging stations provide power to four or five electric motorcycles compared to only one charging spot for an electric car. On the other hand, according to a study conveyed by the University of Comillas Electric Vehicle Observatory the electric motorcycle fleet represent only 19,084 vehicles compared to the 38,949 fleet electric cars[NOREN19].

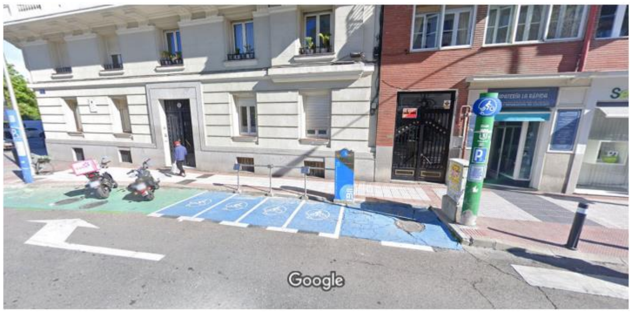


Figure 2.5 Motorcycle charging station [Google Maps]

- On public underground parking:

This type of EV charging is not the cheapest however in comparison with the on-street charging there are plenty of parking spaces, they are usually on great condition and include more types of connectors which make a more convenient and easier the experience for the user. A visual representation of this location can be found in the Thyssen Museum parking shown in figure 3.6 and figure 3.7.

Figure 2.6 Thyssen Parking with EV's [Electromaps]

Figure 2.7 Thyssen Parking empty [Electromaps]

- Shopping centers, Restaurants and Hotels:

According to Expansion newspaper these are the private companies that are devoting resources to the development of the electric vehicle in the city: Iberdrola, Endesa, Ibil-Repsol Saba, Tesla, Fenie-Energía. GIC, Ferrovial amongst others. Endesa: one of the biggest electric companies in Spain has an energetic plan based on strong commercial alliances with parking corporations, shopping centers and restaurants. These alliances include companies like Saba, Empark, Parkia, Carrefour, Decathlon or McDonald's. Endesa's overall project will build 4,300 electric poles in the near future. Iberdrola, direct competitor of Endesa, wants to secure the market of fast, superfast, and ultrafast charging stations (50 kW-150 kW-350 kW) and its great plan will develop 25.000 charging points on a long-term basis[PATIÑO18].

2.2 AVAILABLE FAST CHARGING STATIONS

According to Electromaps Madrid has over 600 locations with charging ports. These locations can provide several ports and, in some cases, different types of them (TYPE 2, Shuko, Tesla Destiny Charger,CCS2…). For this project we are only going to consider the ports that have a public connector with a power of 50 kW and above located in the city of Madrid. The following table includes the district, location, type of location, number of connectors in location, operator, UMTX and UMTY provided by the city council updated by 31st of May 2020.

DISTRITC	Street Location	Type of location	Nº CONNECTORS	OPERATED BY	COORX	COORY	LONGITUDE	LATITUDE
Arganzuela	Calle Chulapos s/n	On public road	1	REPSOL	438893.73	4473226.26	-3.7201631	40.4074098
Arganzuela	Ronda de Valencia 1	On public road	1	GIC	440624.23	4473016.22	-3.6997503	40.4056429
Barajas	Calle Medina del Pomar 22	Others	1	ELECTRIC CHARGE SPAIN	450446.39	4478105.29	-3.584398	40.4521312
Carabanchel	Avenida de la Peseta 6	Gas station	1	REPSOL	434997.82	4468934.81	-3.7656363	40.3684557
Centro	Calle Génova 24	On public road	1	GIC	441259	4475260	-3.6924771	40.425901
Centro	Calle San Bernardo 14	On public road	1	REPSOL	439969	4474882	-3.7076477	40.4224037
Centro	Plaza de Jacinto Benavente 6	Parking	1	EMT	440341.55	4474015.14	-3.7031751	40.4146214
Centro	Plaza de la Cebada	Parking	2	DRIVE THE CITY	439749.07	4473590.81	-3.7101178	40.4107562
Chamartín	Paseo Castellana 160	On public road	1	REPSOL	441528.45	4478870.2	-3.6896332	40.4584423
Chamartín	Calle Cardenal Marcelo Spínola 10	On public road	1	GIC	443204.66	4479841.35	-3.6699516	40.4673071
Chamartín	Calle Hiedra 36	Parking	1	EMT	442442.16	4480402.5	-3.6789963	40.4723097
Chamberí	Paseo Castellana 33	On public road	1	GIC	441547.43	4475930.09	-3.6891388	40.4319578

Chamberí	Paseo Castellana 106	On public road	1	REPSOL	441420.49	4477426.85	-3.6907733	40.4454324
Chamberí	Calle Fernández de los Ríos 42	On public road	1	REPSOL	439847.45	4476302.27	-3.7092149	40.4351894
Chamberí	Calle Fuencarral 114	On public road	1	REPSOL	440414.18	4475676.4	-3.7024748	40.429592
Chamberí	Calle Manuel Silvela 16	On public road	1	GIC	440694	4475775	-3.6991853	40.4305003
Chamberí	Plaza del Conde de Valle de Suchil	On public road	1	REPSOL	440038.83	4475778.21	-3.7069092	40.4304822
Chamberí	Calle Alberto Aguilera 9	Gas station	1	REPSOL	439914.74	4475692.23	-3.7083639	40.4296987
Ciudad Lineal	Calle Bueso Pineda 29	On public road	1	GIC	444431.81	4478363.82	-3.6553478	40.4540798
Hortaleza	Avenida María de Portugal 15	Gas station	1	IBERDROLA	443849.63	4483208.55	-3.6626423	40.4976842
Hortaleza	Avenida de Machupichu 105	Gas station	1	GIC	446082.58	4479561.39	-3.6359822	40.4649769
Puente de Vallecas	Avenida de la Albufera 319	Parking	2	ECOLINERAS	446350.62	4470558.49	-3.6320611	40.3838908
Puente de Vallecas	Avenida Real de Arganda 74	Parking	1	REPSOL	448693.92	4469672.14	-3.6043841	40.3760535
Retiro	Calle Alfonso XII 2	On public road	1	REPSOL	441553.76	4474522.81	-3.6889348	40.4192808
Retiro	Calle Cerro de la Plata 4	On public road	1	GIC	442701.58	4472363.01	-3.6752113	40.399904
Retiro	Plaza del Conde de Casal 6	Parking	2	DRIVE THE CITY	443198.96	4473071.62	-3.6694137	40.4063216
Retiro	Calle Ibiza 1	On public road	1	REPSOL	442444.53	4474433.54	-3.678546	40.418573
Retiro	Plaza de la Lealtad, s/n	On public road	1	GIC	441289,71	4474176.66	-3.692971	40.415881
Salamanca	Paseo Castellana 52	On public road	1	REPSOL	441650	4476325	-3.6879659	40.4355225
Salamanca	Calle Castelló 105	On public road	1	GIC	442261.15	4476262.44	-3.680755	40.4350016
Salamanca	Calle Goya 36	On public road	1	GIC	442227.27	4475141.53	-3.6810526	40.4249016
Salamanca	Calle Goya 123	On public road	1	REPSOL	443066.59	4475108.89	-3.671156	40.4246654
Salamanca	Calle Velázquez 74	On public road	1	REPSOL	442015.28	4475633.05	-3.6835963	40.4293147
Salamanca	Jardines del Descubrimiento	Parking	4	EMT	441474.08	4475110.19	-3.689928	40.4245666
Salamanca	Plaza de Marqués de Salamanca	Parking	1	EMT	442391.2	4475742.85	-3.6791747	40.4303299
Villa de Vallecas	Avenida de Madrid Mercamadrid s/n	Others	2	DRIVE THE CITY	444302.11	4468182.62	-3.6559863	40.362353
Villa de Vallecas	Carretera M602 km. 13	Gas station	1	REPSOL	445890.74	4469312.58	-3.637373	40.3726371
Villa de Vallecas	Carretera Villaverde a Vallecas km. 3,5	Gas station	1	NATURGY	444372.2	4468659.86	-3.6552024	40.366657

Table 2.2Available charging stations [MAD20]

As we can see there are 8 operators that already have charging points on a parking, on street, on a gas station or on other locations. These 8 operators are: Drive The City, Ecolineras, Electric charge, EMT, GIC, Iberdrola, Naturgy and Repsol. The operator with the most connectors is Repsol with a total of 16 connectors on 16 different locations 4 on a gas station and the remaining 12 on street as it is showed on figure3.8.

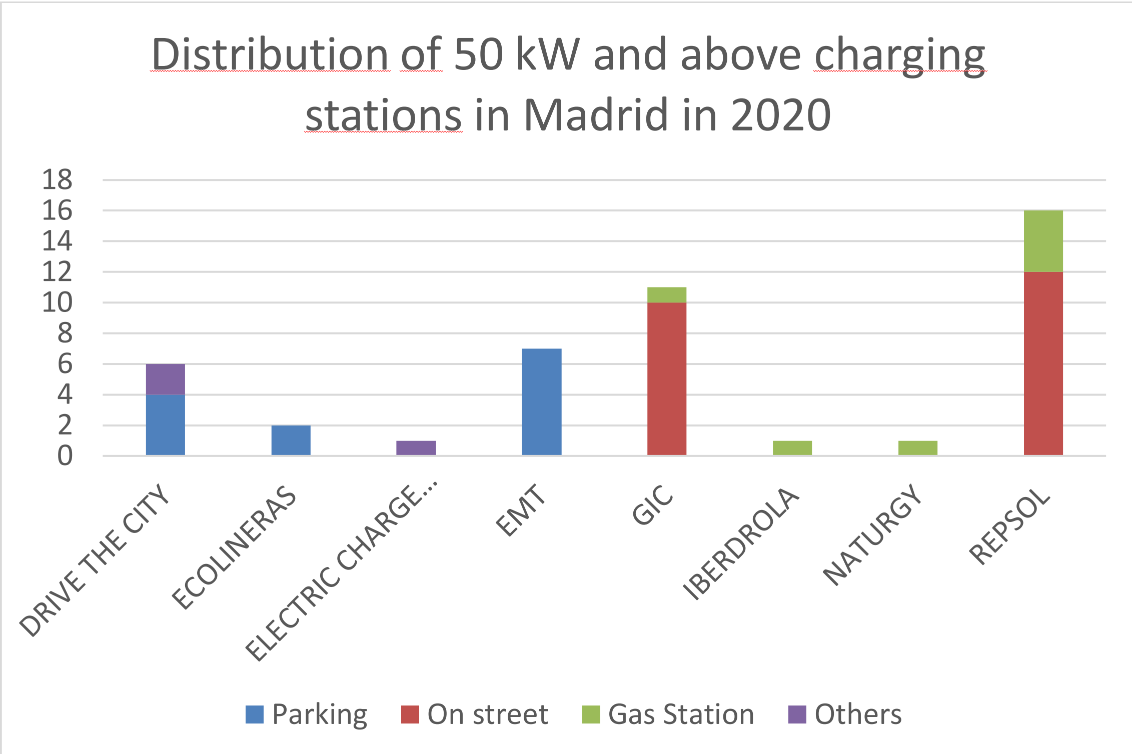


Figure 2.8 Operators of fast charging stations

While electromaps included 80 CHAdeMo connectors and 71 CCS connectors, the city council provided only 45 connectors. This conflict is due to the reason that electromaps provides the statistics of Madrid as a province while the city council only includes those statistics inside the city council's limit. Therefore, for the development and design of the models the information from table 3.2 will be preferred.

3. TECHNOLOGY DESCRIPTION

For the main development of the project several programs have been used to build the data, create graphs, and design the model. The majority of the data for the districts was obtained through the city council web page which provides useful data in Excel sheets per district and neighborhood such as population, area of the neighborhood, density of population, and many more information that was not relevant for this project. First, we must define all the possible nodes that form the grid that will be used in the problem. In our case the grid will be formed by all the neighborhoods (131) in the city plus the charging stations that already exist (38) with a total of 169 nodes. Once all nodes are determined, we include them in an excel sheet with their correspondent UMTX and UMTY coordinates. These coordinates are used to obtain the distance between nodes. To annex the UMTX and UMTY coordinates from each neighborhood a point selected by hand using google maps was placed on the center of the neighborhood. All the remaining information comes from the Excel sheet provided by the governmental institution. All the crucial information was collected into one Excel sheet that would be read afterwards on MATLAB. The final document named “Alllocations.xlsx” stores the information of the neighborhoods (rows 1 to 131) as well as the previously existing fast charging stations (rows 131 to 169). Once the information is properly collected, MATLAB would read the document using the function xlsread and would be stored on a variable called “data”.

```
data=xlsread('Alllocations.xlsx');
```

This function will read the Excel file and create a matrix similar to the Excel document, however the function only reads numeric data so the character strings would be considered not a number(nan).

The document “Alllocations” include the following 9 columns with the data provided from Madrid’s city council:

1. District
2. Neighborhood name
3. Neighborhood number

4. Neighborhood Latitude

5.Neighborhood Longitude

6. Neighborhood Area

7. Neighborhood density Habitants per hectare as of 01/01/2018

8. Neighborhood population

9.Neighborhood cars as of Dec 2017

After the document is read with the 'xlsread' function, the number of rows and columns of the document can be obtained using the function 'size(Matrix, num)' where 'Matrix' is the matrix that we want to know the number of rows or columns and num is either 1 or 2 being 1 if we want to obtain the number of rows and 2 if we want to know the number of columns in the matrix.

```
nodes = size(data,1);% count number of rows
columns = size(data,2);%count number of columns
```

These parameters are useful for future loops and the benefit of using 'size' instead of a static number is that any document independently of the number of rows and columns can be operated with the same MATLAB code. For example, in case the grid is updated with new information or new nodes.

The matrix of coordinates can be represented with the map below. The map made with My Maps by Google contains different color markers each color represents a different district.

Figure 3.1 My maps Neighborhoods

Using My Maps as well the figure 2.2 shows with blue marks a visual representation of the already existing fast charging stations in the city.

Figure 3.2 MyMaps already available charging stations

To determine optimal location of charging stations the distance between nodes must calculated. To do so, we use the Haversine formula using the earth radius and the UMTX and UMTY coordinates. The equation is the following:

$$d = 2r\ arcsin\left(\sqrt{sin^2(\frac{\Phi_2 - \Phi_1}{2}) + cos(\Phi_1)cos(\Phi_2)sin^2(\frac{\lambda_2 - \lambda_1}{2})}\right)$$

Where:

d = distance between 2 nodes

r = Earth's radious (6.371 Km or 3958.8 miles)

Φ_2 = latitude of node 2

Φ_1 = latitude of node 1

λ_2 = longitude of node 2

λ_1 = longitude of node 1

Once the distance matrix is obtained, we determine a critical distance that will reflect the largest distance between one EV station and the furthest one so that all the area is covered.

In order to do so in MATLAB two for loops run the distance matrix and with an if case the distance of the nodes ij (I is the number of rows and j is the number of columns) is compared to the critical distance that has been mentioned before .

The function "intlinprog" performs the optimization problem when it is provided with the number of less or equal than constraints as well as the number of equal constraints, the upper and lower bounds, the objective function and the number of variables that are integers.

```
[X,Z]=intlinprog(f,int,[A1;A2;A3;A4],[b1;b2;b3;b4],Aeq,beq,lb,ub)
```

Where

X = vector with the final value of the decision variables

Z = final objective value

f = row vector that contains the objective function

int = row vector that constains the integer variables

A = matrix, right hand side of the less or equal than constraints

b = column vector, left hand side of the less or equal than constraints

Aeq = matrix, right hand side of the equality constraints

beq = column vector, left hand side of the equality constraints

lb = row vector, lower bound of each variable

ub = row vector, upper bound of each variable

Finally, since the first row of the excel file is not read on the MATLAB matrix due to be categorical only(node, district, UMTX,UMTY) the final node conclusion is added one position

4. PROJECT DESCRIPTION

4.1 JUSTIFICATION

The investment on charging stations bring multiple benefits, it provides a better network of charging stations that users demand before they buy an electric vehicle. Noise reduction and carbon dioxide emissions reduction are also some of the benefits that electric vehicles have compared with standard diesel or gas vehicles. This report is aimed to help the local community of Madrid to promote the electric vehicle and push to a greener city transition.

New legislation such as Madrid Central or the different benefits that electric vehicles or Eco vehicles have with the different distinctives such as free parking anywhere on the city or public parking payment reductions are also inviting Madrid's citizens to understand that moving to electric is a possibility and with roper infrastructure it can bring the greener future much sooner.

The objective of the project is to design a location model for direct current fast charging stations. To do so, different sub models will be designed attending the previous existing fast charging stations in the city, estimated traffic of EV vehicles in those stations and traffic regulation. Using operation research techniques can serve as a guidance when developing and building future charging stations. It allows locations that could have been not though before to be crucial to the network as each node depends on the other nodes. It also presents a final look of a network which favors a more guided look on how the future network should be represented. The model is dynamic as new constraints or nodes can be included as different requirements or necessities come along.

4.2 METHODOLOGY

As mentioned before, the purpose of this study is to locate the optimal location of fast charging posts on Madrid city using research operation techniques. Similar problems to the one studied on this research would be the optimization on the location of logistic warehouses or location problem with other kind of restrictions.

These similarities can be appreciated on a study done by professor Sysoiev from the Kharkiv Polythecnic Institute on “Optimizing the Number and Location of Warehouses in Logistics Networks Considering the Optimal Delivery Routes and Set Level of Reserve Stock” [SYSOI13]. Another similar study is the one conveyed by the Portland state University on” Maximum coverage capacitated facility location problem with range constrained drones” [CHAUH19] and to name one last one with a different approach using artificial intelligence by the School of Geography and Planning on “Where will the next emergency event occur? Predicting ambulance demand in emergency medical services using artificial intelligence”[LIU19].

For calculations and the core development of the project I will be using MATLAB. MATLAB can be used for many purposes besides calculations for example obtaining graphs and matrix visualization. It is compatible with other text programs such as notepad, Excel, and many more. For data gathering and filtering I will be using Excel, it provides a fast-visual representation of the data that will be read with MATLAB. Finally, other office programs such as PowerPoint and Word become great tools when looking for more detailed graphs and tables.

4.3 COST ANALYSIS

According to the U.S.Department of Energy report on Costs Associated with non-residential electric vehicle supply equipment (2015) [USDOE15],the costs associated with the development and operation of a charging station include: unit hardware costs, installation costs, operation and maintenance costs, additional cost factors and public costs.

4.3.1 UNIT HARDWARE COSTS

These costs include the charging station unit as well as optional features such as Bluetooth, NFC card readers … The cost of the unit depends on the type of unit that will be installed (charging level and amperage rating, number of ports, connectivity…). The single port unit cost ranges from 300$ to 1500$ for Type 1, 400$ to 6,500$ for Type 2 and $10,000 to $40,000 for fast charging DCFC type. Additional features such as energy monitoring, retractable cords or communication capabilities will also incur on the cost of the unit.

4.3.2 INSTALLATION COSTS

Installation costs include contractor labor and equipment for the connection to the electrical service, additional installation of electrical services and components such as transformers, traffic protection, lightning, engineering review and permissions. The installation costs ranges for level/type 1 up to 3000$, level/type 2 installation costs ranges between 600$ and 12,700$ with an average cost of 3,000$ and DCFC installation cost ranges between 4,000$ and 51,000$ with an average installation cost of 21,000$.

4.3.3 OPERATION AND MAINTENANCE (O&M) COSTS

O&M costs include electricity consumption, routine maintenance, subscription to additional features, billing costs, repairs… Electricity rates range from $0.08 to $0.15 per kWh. Connectivity and Wi-Fi fees range from 100$ to 900$ annually. The operator should also include a quantity reserved for vandalism or misuse of the unit, replacement of damaged components or software malfunction.

4.3.4 PUBLIC AND ADDITIONAL COSTS

Public and additional costs include the costs incurred on visibility and signage, advertising, the requirement of permissions, inspections, engineering designs, incentives…

5. MODEL DEVELOPMENT

The internal distribution of this chapter is structured on the description and analysis of the geographic distribution of the grid of the city, the distribution of vehicles in the city centered on the electric vehicle market and finally how the demand was estimated using traffic data entering the city as well as the percentage of electric vehicles in it.

5.1 GEOGRAPHIC DISTRIBUTION

The city of Madrid is formed by the 21 districts showed in figure 5.1. To determine the possible locations where new stations can be built first, we will have to elaborate a coordinate map containing each location possible. Originally, instead of having every point on the map of the city of Madrid's road a good approximation could be providing only the coordinates of the doorways of every building in the city of Madrid. However, a node reduction had to be made due to the limitation of computing power. A new type of grid was selected to ensure a node reduction associating each node to each neighborhood of the city.

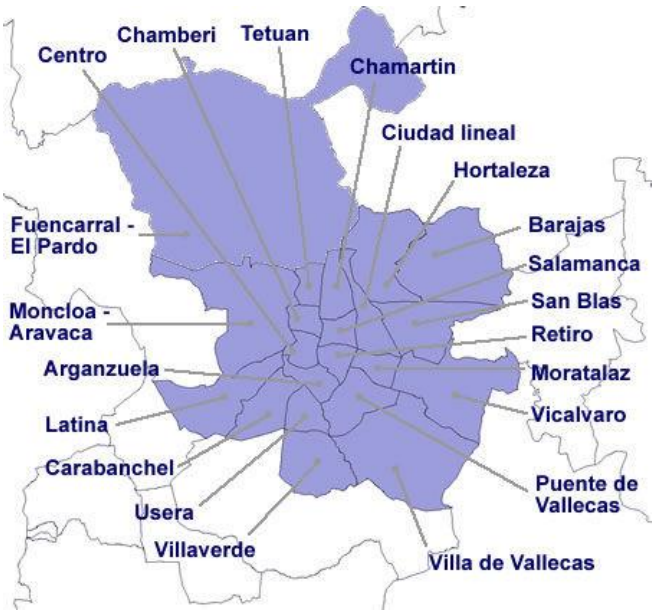


Figure 5.1Madrid's districts. Source gifex

With a total number of 131 neighborhoods across the 21 districts Madrid's grid would have a reasonable compromise between location effectiveness and computing power. A more detailed description of the neighborhoods with the name, number, relative location on the district and location on the city is presented on Annex B.

5.2 VEHICLES OF STUDY

The data provided by the DGT (*Dirección General de Tráfico)* provides information about the different vehicles that form the Spanish vehicle fleet. It also categorizes those vehicles into the 50 provinces and two autonomous cities that form Spain and as well differentiating based on the type of fuel. Other relevant information added is the car distinctives that each province has.

The vehicles are divided in different types, trucks, vans, buses, cars, motorcycles, industrial tractors, trailers, and other vehicles. It would be interesting to differentiate between a company BEV and a consumer BEV. A company BEV include electric logistic vehicles such as UPS or FedEx, some supermarkets deliver food to your home using BEV vehicles, car sharing companies (Wible, Car2go, Zity…) and passenger transportation companies also include some electric vehicles on their fleet. However, this distinction is not present on the document and therefore it is not considered.

As we can see on figure 5.2, cars make 77% of the total vehicles of Madrid. That 77% includes 1,703,888 gasoline cars (44%), 2110664 diesel cars(54%) and 51510 other type of propulsion cars such as gas powered or electric (2%).

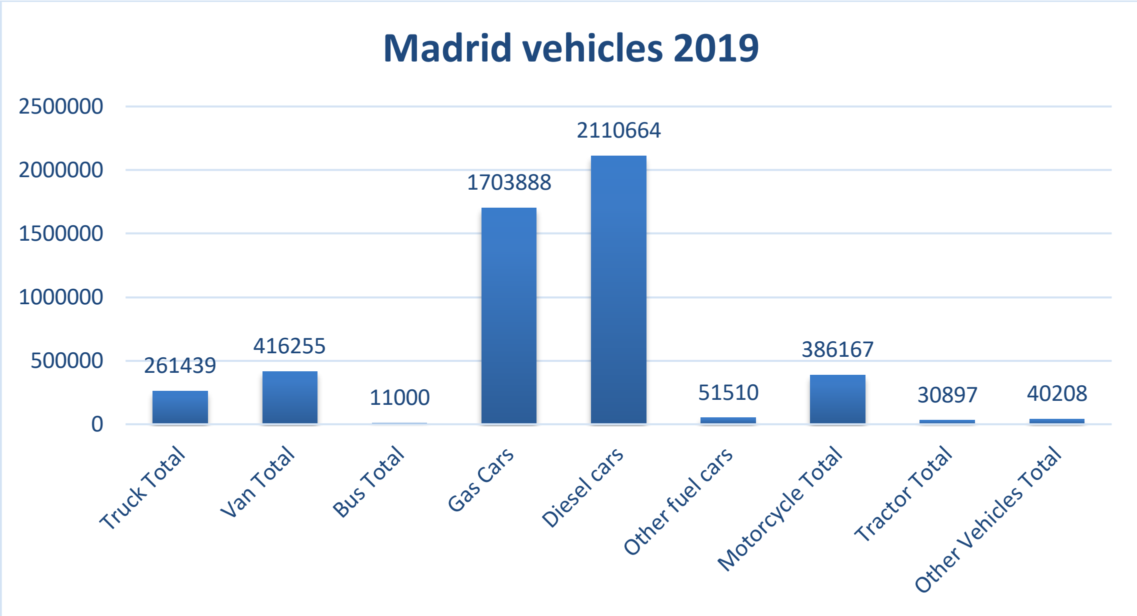


Figure 5.2 Madrid's vehicle categorization. Source DGT

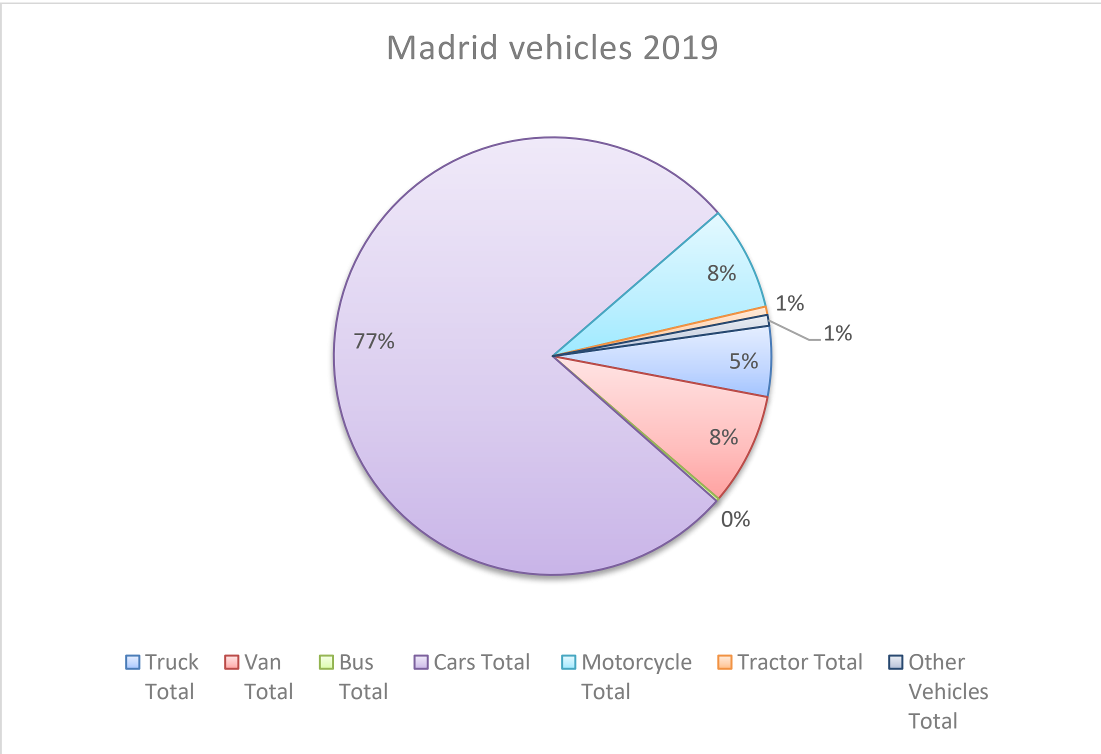


Figure 5.3 Pie chart vehicle distribution. Source DGT

To determine the battery to charge in these charging stations, we should define a standard vehicle that is most common in Spain. According to the data provided by the University of Comillas [NOREN19] the most common BEV car in Spain is the Renault Zoe followed by the Nissan Leaf taking a similar portion of the market with 15% and 14% respectively. These two vehicles share a lot of similarities that make them convenient for the city use.

They have a relatively compact size with 4-4.5m long . The Nissan Leaf uses a TENKA 40 kWh battery while the Renault Zoe uses a 52 kWh battery while the Nissan can reach up to 62 kWh battery, however due to car dimensions and power delivered, the Zoe can last slightly longer on the road with a 402 km autonomy compared with the Nissan that can last 385 km. We must also mention that these two vehicles come with different price tags as well. The Leaf prices around 25.500€ and the Zoe prices at around 21.500€.

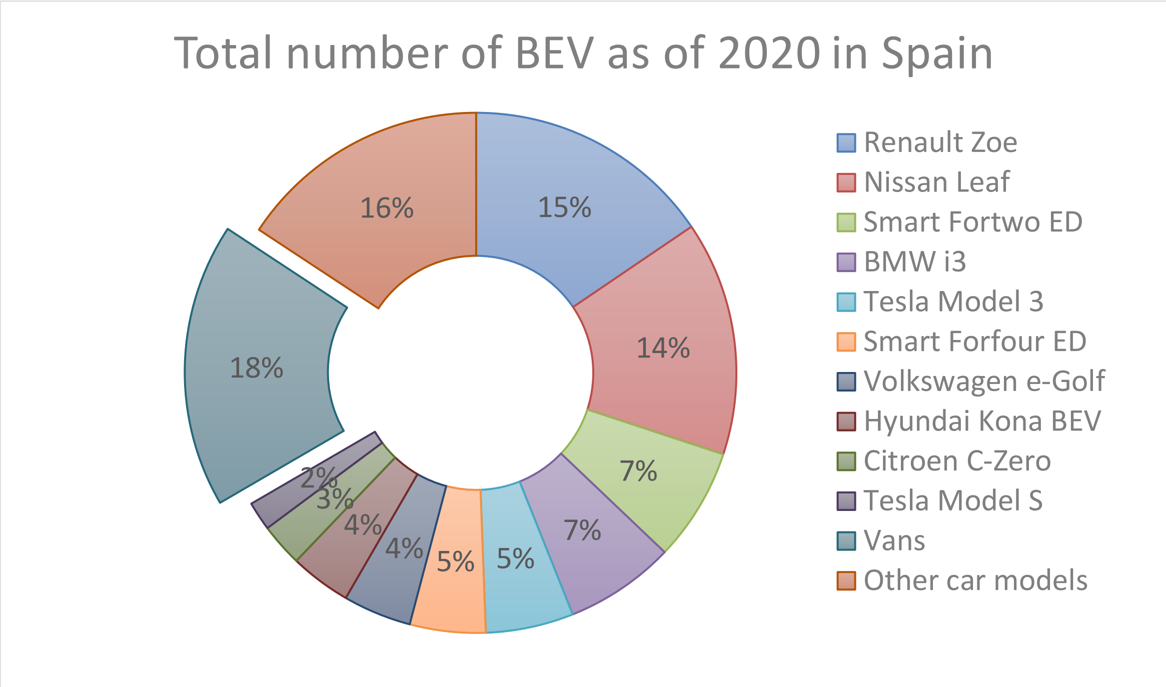


Figure 5.4 BEV in Spain. Source DGT and [NOREN19]

If we take a closer look to what are the most common EV's in Spain in 2019 the two most common BEV's are The Nissan Leaf (5,442 vehicles) and the Renault Zoe (5,790 vehicles) which combined take 36.5% of the BEV car Market and almost a third of the total BEV market .Due to their similar characteristics we can use the Renault Zoe as the standard. On the other hand, the PHEV market is controlled by the Mitsubishi Outlander PHEV (4,389 vehicles) taking almost quarter of the PHEV market so it can be considered the standard of the PHEV's. The Mitsubishi has a battery of 13.8 kWh which represents ¼ of the battery of our standard BEV the Renault Zoe.

5.3 DEMAND

To measure the demand of the city the DGT(*Dirección General de Trafico*) provides information regarding the flow of the vehicles entering the city is used. At moment of confinement, the data from the cameras was corrupted as there is minimum traffic, therefore historical data from the 12th of June was used to represent a more accurate standard traffic flow. This camera provides information of the average speed occupancy end the traffic flow. The traffic flow is provided hourly, diary, weekly or monthly. The demand is historically defined with at least one soft and an overall high peak at some point of the day depending on the road. A conservative approach for the demand would acknowledge the worst possible scenario which will be considering the traffic of that road as the highest traffic throughout the day. Not all cameras listed on the web page can provide the traffic information and the ones that do and surround the traffic coming in and out of the city are located on ANNEX C Incoming traffic to Madrid.

Looking at the data provided by the DGT, only 0.2% of the total number of cars in Spain are electric. In MATLAB we associate this factor with the parameter ev. Out of the total number of vehicles: trucks, vans, motorcycles, cars and other vehicles, cars represent the 82% represented in MATLAB with the parameter clv.

Afterwards, the traffic flowing through each main entrance to the city is also designated to a parameter to determine the overall demand of ev cars in the city. With the available information from the intensity vehicles in the entrances and additional information that some of the cameras include such as the percentage of the vehicles that are cars.

Using the traffic data of vehicles from each entrance into the city, the number of vehicles that exist already in a neighborhood according to the information from the city council and to the percentages of electric cars calculated in each case we can infer an approximate daily demand. Since the locations are going to be a fixed point the demand will be calculated using the highest data point from each road.

The daily intensity of the roads as well as the location of the road intensity tracker is defined in more detail in the Annex C ‘Incoming traffic to Madrid’. There are five main entrances to the city that we have dived them in sections North West (NW), North East (NE), West(W), South(S) and East(E) represented by the roads A-6 Pk 3.5C, M40 Pk 5.45C, A-5 Pk 10.69C A-42 Pk 5.8C, A-2 Pk5.5C correspondingly.

The districts are categorized in North East South and West to attend the demand mentioned.

North: District 5, District6, District 8, District 15, District 16, District 21.

East: District 3,District 4, District 14, District 19, District 20.

South: District 2, District 11, District 12, District 13, District 17, District 18

West: District 1, District 7, District 9, District 10

To assign the correct demand to each neighborhood, we need two for loops and an if case. The first for loop reaches the total number of neighborhoods that we have previously counted with the function size. Afterwards another for loop is presented for each cardinal point (North, West, South, East). This loop moves from one to the number of neighborhoods that correspond to the districts designated to the cardinal point. For example, the vector North contains 42 numbers corresponding to the 42 neighborhoods that we have categorized as North.

North=[32 33 34 35 36 36 37 44 45 46 47 48 49 50 51 52 53 26 27 28 29 30 31 101 102 103 104 105 106 92 93 94 95 96 97 98 99 100 127 128 129 130 131]

These numbers in the vector represent the relative position in the Excel document were the neighborhood is located. For example, the number 32 in the vector North is not the 32nd neighborhood but the position 32 in the excel document which contains the neighborhood 56 Castilla.

Assuming Pareto's Law 20% of the total traffic of EV in Madrid is estimated to charge on peak time and with the new infrastructure a conservative 30% of those remaining EV would predictably charge on DCFC.

6. RESULTS ANALYSIS

6.1 MODEL 1

First the program is performed without the existing 38 EV stations and for two different critical distances 1km and 2km. A very conservative distance compared to the minimum distance of 200m for gas stations from households. Maximum coverage location problem assuming two different critical distances(D=1Km, 2Km):

6.1.1 MODEL 1.1 D=1KM

Minimize $\sum_i X_i$

Subject to: $\sum_i a_{ij} X_i \geq 1 \quad \forall \ j \in \mathbf{N}$

$X_i = 0,1 \quad \forall \ i \in \mathbf{N}$

Where

$$Xi \begin{cases} 1 \ if \ an \ EV \ station \ is \ located \ on \ node \ i \\ 0 \ otherwise \end{cases} \quad \forall \ i$$

$$a_{ij} \begin{cases} 1 \ if \ node \ i \ is \ under \ the \ critical \ distance \ D \ from \ node \ j \\ 0 \ otherwise \end{cases}$$

$N = \{1,2,3\ldots131\} \ (nodes)$

Final solution 83 Nodes corresponding to the following neighborhoods:

16 21 22 24 25 31 35 42 51 52 55 62 63 71 74 81 82 83 84 85 86 87 88 91 94 95 96 97 101 103 104 105 106 107 111 115 116 117 121 123 124 125 131 132 134 136 141 142 146 151 152 154 157 159 161 162 163 164 171 172 173 174 181 182 183 191 192 193 194 203 205 206 208 211 212 213 214 215

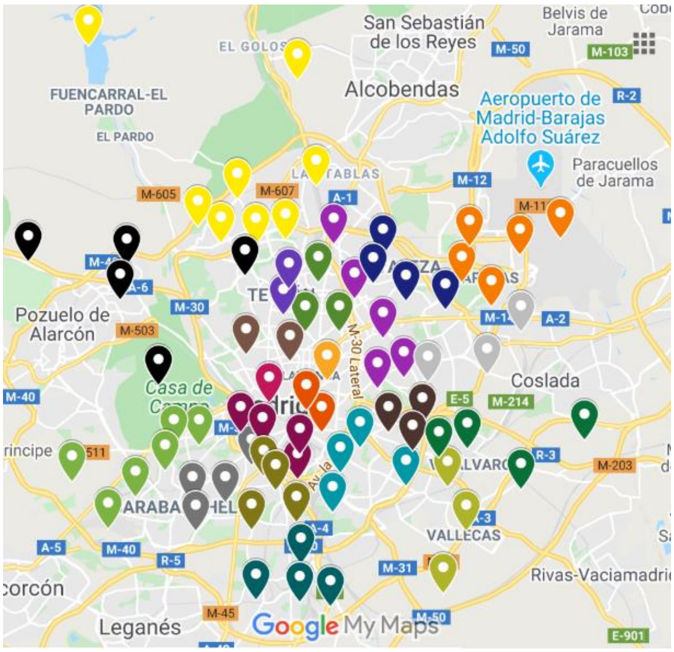


Figure 6.1Final Distribution Model 1.1

Developing 83 charging stations out of 131 possible locations would require high investment and a more coherent distance would be 2km. As the figure shows, there are some regions with more distance than others, for example some areas of district 18 are not covered because the district is only divided into 3 neighborhoods taking each one a vast surface area. To check that the program has performed well even on unclear areas such as between district 10 and 11 we can review the node distance to see if any of the adjacent nodes that have a charging station on them are within the critical distance of 1km. To be more specific, neighborhoods 113 and 112 are withing 1km distance from neighborhoods 101 and 117 correspondingly.

6.1.2 MODEL 1.2 D=2KM.

The optimal solution with this new critical distance is 31 EV stations located at the following neighborhoods:

21 42 65 73 81 82 86 87 88 91 93 96 97 105 106 114 124 132 143 156 165 166 172 181 182 191 194 202 213 215

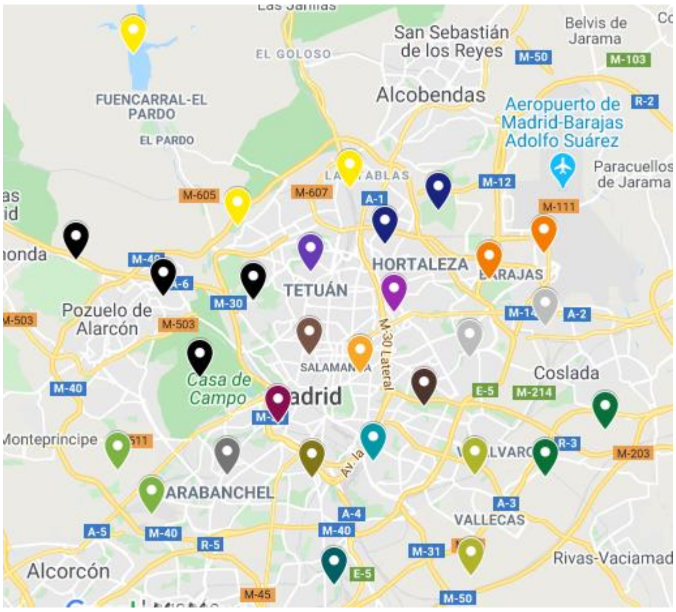


Figure 6.2 Final Distribution Model 1.2

With a wider range the number of EV stations decreases by about 60 percent. This type of model does not consider the differences in the demand that may have for example in the city center compared to the outdoor areas of the city. This factor makes the EV stations approximately evenly spread ensuring an EV station on the outside areas where neighborhoods take much larger surface area.

6.2 MODEL2

Once the problem is understood a good upgrade of the model would be introducing the EV stations that already exist. The problem will consider the charging stations provided by Madrid city council which provide a power capacity 50 Kw or higher.

6.2.1 MODEL2.1 D=2KM

Minimize $\sum_i X_i$

Subject to: $\sum_i a_{ij}(X_i + K_m) \geq 1 \quad \forall\ j \in \mathbf{N}\ \forall\ m \in \mathbf{M}$

$X_i = 0{,}1 \quad \forall\ i \in \mathbf{N}$

Where

$$Xi \begin{cases} 1\ if\ an\ EV\ station\ is\ located\ on\ node\ i \\ 0\ otherwise \end{cases} \forall\ i$$

$$a_{ij} \begin{cases} 1\ if\ node\ i\ is\ under\ the\ critical\ distance\ D\ from\ node\ j \\ 0\ otherwise \end{cases}$$

$K_m = number\ of\ connectors\ at\ station\ M$ (parameter)

$M = \{1,2,3,\ldots 38\}$ (charging stations already available)

$N = \{1,2,3, \ldots 131\}$ $(nodes)$

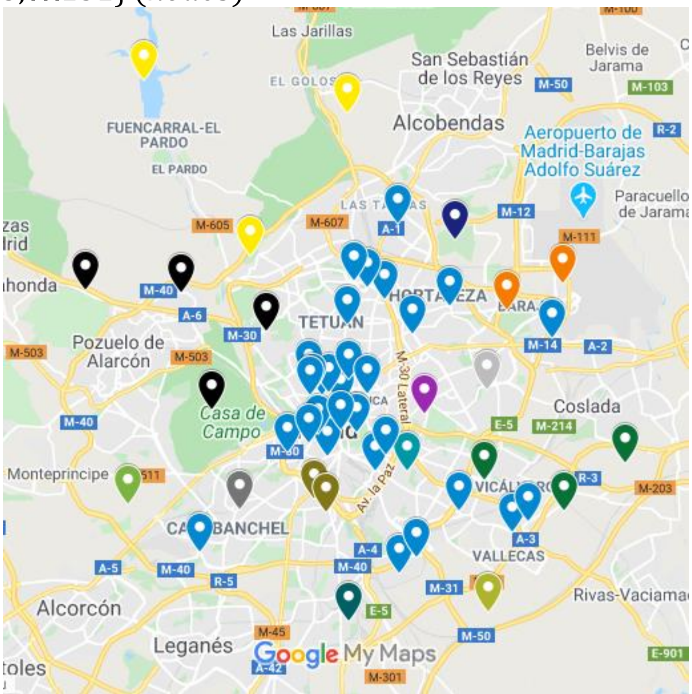


Figure 6.3 Final Distribution Model 2.1

The distribution seems clear, some neighborhoods such as 124 and 125 from the district 12 in the south of the city appear rarely close from one another. Checking manually that all nodes around that area are covered we can confirm that there is no mistake and that this is the optimal solution. There may be other solutions but in the end the optimization of the objective function should have an equal or bigger number of EV stations to develop.

The final solution determines that the new stations should open 21 charging stations on the following neighborhoods:

81 82 88 91 93 95 96 105 114 124 125 136 151 166 172 181 191

The final objective function is 60 locations with a total of 67 ports assuming 1 port for the new locations and the ports given from the city council at each charging station that is already on operation.

6.2.2 MODEL2.2 D=1KM

Minimize $\sum_i X_i$

Subject to: $\sum_i a_{ij}(X_i + K_m) \geq 1 \quad \forall \; j \in \mathbf{N} \; \forall \; m \in \mathbf{M}$

$X_i = 0{,}1 \quad \forall \; i \in \mathbf{N}$

Where

$$Xi \begin{cases} 1 \; if \; an \; EV \; station \; is \; located \; on \; node \; i \\ 0 \; otherwise \end{cases} \forall \;\; i$$

$$a_{ij} \begin{cases} 1 \; if \; node \; i \; is \; under \; the \; critical \; distance \; D \; from \; node \; j \\ 0 \; otherwise \end{cases}$$

$K_m = number \; of \; connectors \; at \; station \; M$ (parameter)

$M = \{1,2,3,\ldots 38\}$ (charging stations already available)

$N = \{1,2,3,\ldots 131\} \; (nodes)$

Objective function 106 locations, therefore 68 new locations must build a charging station and a total number of connectors 113.

Neighborhoods to develop new charging stations:

23 24 52 55 61 64 81 82 83 84 86 87 88 91 93 94 95 96 97 101 103105 106 107 111 114 116 117 121 123 124 125 131 132 135 136 141 142 144 146 151 152 154 161 162 163 164 166 171 172 173 174 181 182 191 192 193 194 203 205 206 208 212 213 214 215

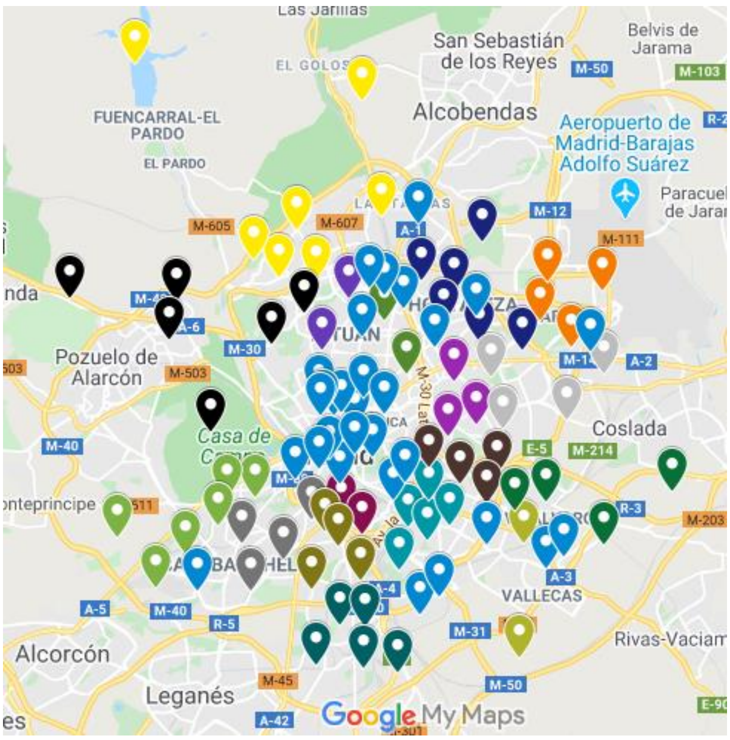


Figure 6.4 Final Distribution Model 2.2

This new configuration requires more than three times the number of new charging stations compared with the critical distance of 2km. On the other hand, this configuration ensures that all districts have at least one charging station inside the limitations of the district.

6.3 MODEL 3 D=1.5KM

The previous models provide a great design for an optimal maximum area coverage from each EV station, but it does not directly consider the demand of the city. To do so the next model is proposed.

After designating each neighborhood to a side of the city (North, East, South, West) we calculate the total traffic of the neighborhood using the number of vehicles provided by the city council as of the end of 2017 as well as the vehicle flow of the entrance roads in to the city. The final demand of EVs at peak is presented on figure 6.5:

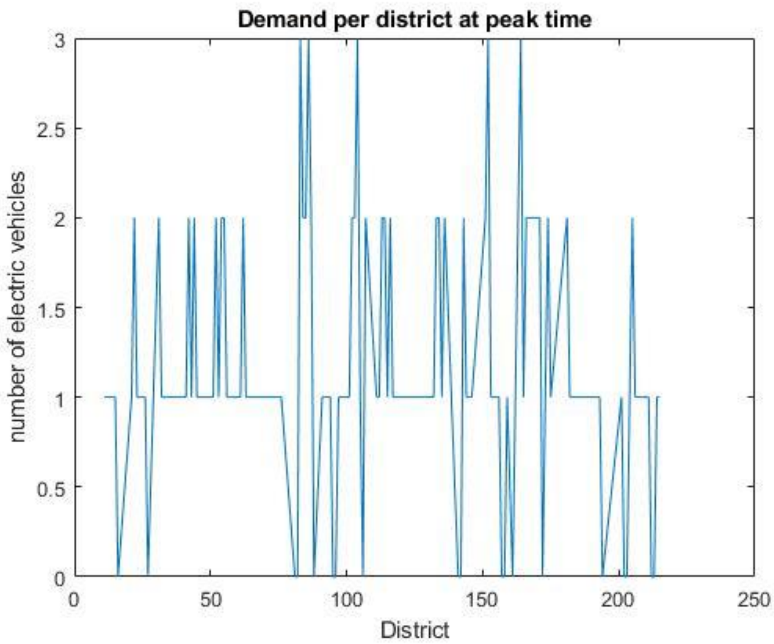


Figure 6.5 Demand per district at peak time

Formulation:

Minimize $\sum_i X_i$

Subject to:

$$\sum_i a_{ij}(X_i + K_m) \geq 1 \quad \forall\ j \in \mathbf{N}\ \forall\ m \in \mathbf{M}$$
$$\sum_i a_{ij} Y_i \geq R_i \quad \forall\ j \in \mathbf{N}$$
$$\boldsymbol{Y_i \leq 2 * X_i} \ \forall\ i \in \mathbf{N}$$
$$\sum_i Y_i \geq \sum_i R_i \quad \forall\ j \in \mathbf{N}$$
$$X_i = 0{,}1 \quad \forall\ i \in \mathbf{N}$$
$$Yi = 0{,}1{,}2\ \forall\ i$$

Where

$$Xi \begin{cases} 1\ if\ an\ EV\ station\ is\ located\ on\ node\ i \\ 0\ otherwise \end{cases} \forall\ i$$

$Yi = number\ of\ connectors\ per\ station\ i\ \forall\ \ i$
$Ri = number\ of\ vehicles\ that\ demand\ charge\ at\ node\ i\ \forall\ \ i$
$a_{ij} \begin{cases} 1\ if\ node\ i\ is\ under\ the\ critical\ distance\ D\ from\ node\ j \\ 0\ otherwise \end{cases}$
$K_m = number\ of\ connectors\ at\ station\ M$ (parameter)
$M = \{1,2,3, \ldots 38\}$ (charging stations already available)
$N = \{1,2,3, \ldots 131\}\ (nodes)$

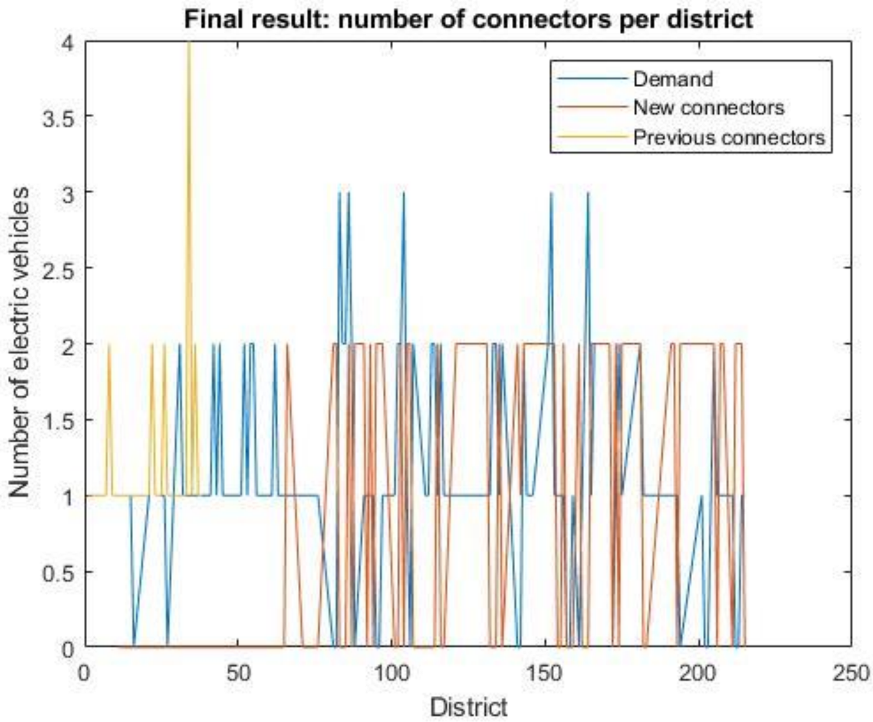


Figure 6.6 Final result: number of connectors per district

53 new charging stations should be built on the following neighborhoods:

066 81 82 86 88 91 93 95 96 97 103 105 106 115 121 122 123 124 125 126 127 131 135 141 142 143 144 145 146 151 152 153 156 161 165 166 171 173 175 181 191 192 194 201 202 203 204 205 207 208 212 213 214

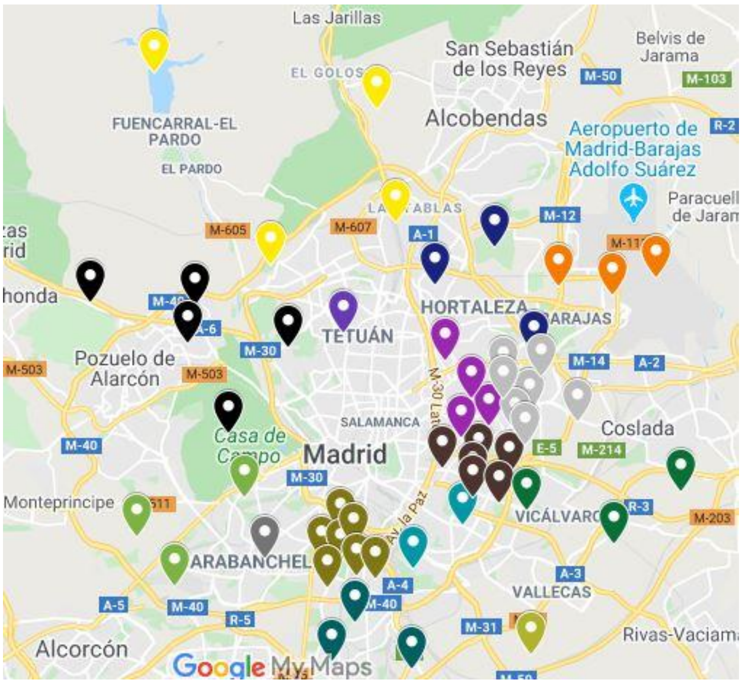


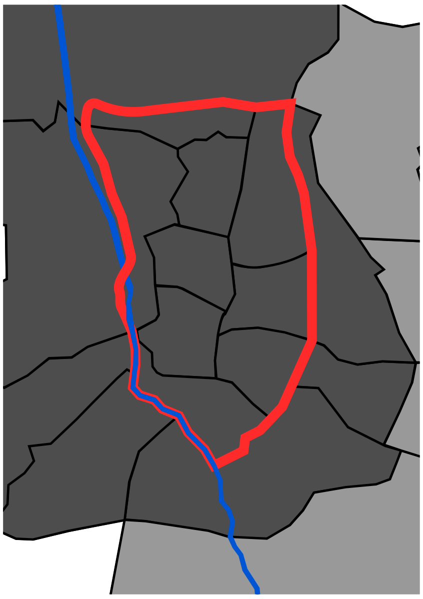
Figure 6.7 Final Distribution Model 3

As the figure shows, most of the new nodes to develop are located on the outside areas of the city with a higher density on the east side of the city where there is no existing supply for the existing demand in districts such as *Usera*(12), *Moratalaz*(14) or *San Blas de Canillejas*(20). According to the demand at peak time, not all nodes require the same number of connectors. The number of connectors that each station can have has been limited to 2 since the average number of connectors at high speed charging stations ranges between 1 and 2. Almost every new charging stations requires of 2 connectors besides *Horcajo's* neighborhood (142) that would only require 1 connector.

6.4 MODEL 4 D=1.5KM

Finally, to consider the new regulations of the city council the model should include different costs to the neighborhoods under the Madrid Central area, Under the M30 area, and the remaining areas. A good cost estimation could be:

- Cost of 1 unit for neighborhoods under the Madrid Central area
    - All neighborhoods from district 01
- Cost of 2 units for neighborhoods under the M30 area



- 01 Centro
- 02 Arganzuela
- 03 Retiro
- 04 Salamanca
- 05 Chamartín
- 06 Tetuán
- 07 Chamberí

Figure 6.8 M-30 Belt. Source Wikipedia

- Cost of 3 units for neighborhoods outside of the M30 area

Formulation:

Minimize $\sum_l X_l + 2 * \sum_g X_g + 3 * \sum_f X_f \quad \forall\ l \in \mathbf{L}\ \forall\ g \in \mathbf{G}\ \forall\ f \in \mathbf{F}$

Subject to:

$$\sum_i a_{ij}(X_i + K_m) \geq 1 \quad \forall\ j \in \mathbf{N}\ \forall\ m \in \mathbf{M}$$
$$\sum_i a_{ij} Y_i \geq R_i \quad \forall\ j \in \mathbf{N}$$
$$\boldsymbol{Y_i \leq 2 * X_i} \ \forall\ i \in \mathbf{N}$$
$$\sum_i Y_i \geq \sum_i R_i \quad \forall\ j \in \mathbf{N}$$
$$X_i = 0,1 \quad \forall\ i \in \mathbf{N}$$
$$Yi = 0,1,2\ \forall\ i$$

Where

$$Xi \begin{cases} 1\ if\ an\ EV\ station\ is\ located\ on\ node\ i \\ 0\ otherwise \end{cases} \forall\ i$$
$Yi = number\ of\ connectors\ per\ station\ i\ \forall\ i$

$Ri = number\ of\ vehicles\ that\ demand\ charge\ at\ node\ i\ \forall\ i$

$$a_{ij} \begin{cases} 1\ if\ node\ i\ is\ under\ the\ critical\ distance\ D\ from\ node\ j \\ 0\ otherwise \end{cases}$$
$K_m = number\ of\ connectors\ at\ station\ M$ (parameter)

$M = \{1,2,3, \ldots 38\}$ (charging stations already available)

$N = \{1,2,3, \ldots 131\}$ $(nodes)$

L={1,2,3,4,5,6}(Madrid central nodes)

G={7,8,9…42,43}(M-30 nodes)

F={44,45,130,131}(Remaining nodes)

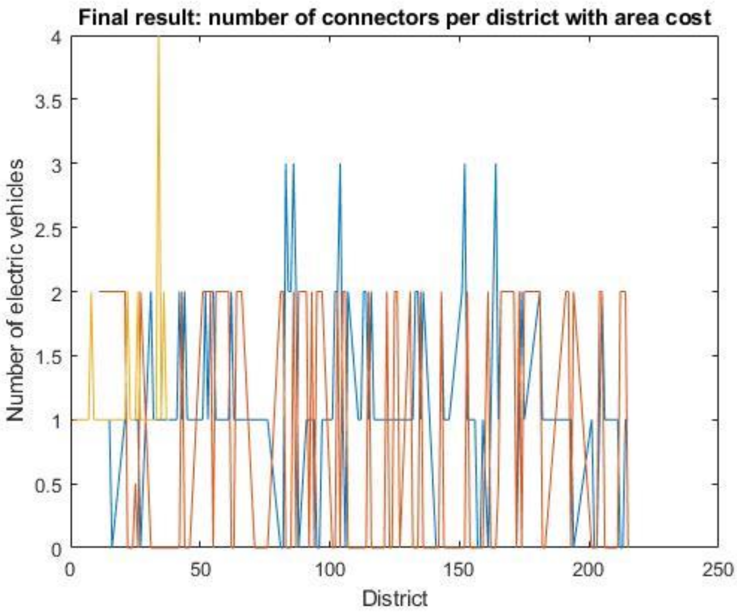


Figure 6.9Number of connectors per district with an associated area cost

54 new different charging stations should be built.

11 12 13 14 15 16 21 25 27 43 51 52 53 54 56 61 64 65 66 81 82 86 88 91 93 95 96 97 103 105 106 115 122 125 126 131 135 143 153 161 165 166 171 173 175 181 191 192 194 204 205 212 213 214.

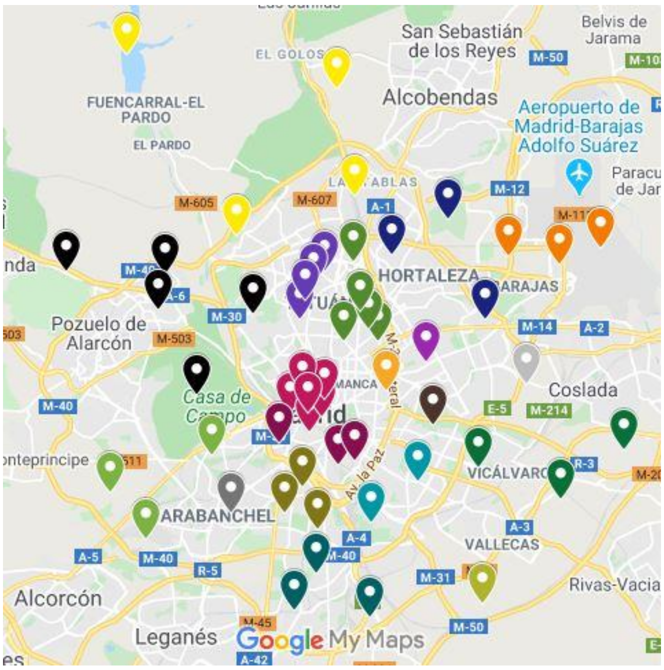


Figure 6.10 Final Distribution Model 4

The model includes three new high-density areas on *Centro*, *Tetuan* and *Chamartín* districts. It makes sense as the cost of developing one charging station on *Centro* is either half or one third the cost of developing it on other areas. Areas that are outside of the M-30 still have over 60% of the locations to be built because there is no reach from previous DCFC on those areas and they are separated great distances from each other.

7. CONCLUSIONS AND FUTURE WORKS

7.1 CONCLUSIONS

The project has developed different models according to different restrictions that could suit different priorities when building new charging stations for the future. The last model reflects the best behavior of the city as it considers the traffic location, the number of cars per neighborhood to estimate the demand as well as considering the new traffic regulations that has been stablished with Madrid Central area and M30 area.

The most relaxed model got an optimal number of 21 new locations while the most constrained model calculated an optimal number of 83 new locations. As all of the models included a distance constraint of 1Km,1.5Km or 2Km neighborhoods usually located on the outside part of the city with great area coverage such as *El Pardo* (81) or *Casco Historico de Vallecas* (181) are present on all models since there are no existing fast chargers on those areas and the distance is not covered with new stations in other neighborhoods.

Model	Critical distance	New Charging Stations	Characteristics
1.1	1Km	83	Too many new locations, a lot of neighborhoods are further apart from 1Km
1.2	2Km	31	Visually even distribution across the city, more feasible to develop than the model 1.1
2.1	2Km	21	Most charging stations located outside the M-30

			as the existing ones are located near the center
2.2	1Km	68	Still a very high number of new locations, fills almost all neighborhoods outside the M-30 which does not seem necessary
3	1.5Km	53	The demand emphasizes the new locations on the southern and eastern parts of the city
4	1.5Km	54	The most complete model considering demand and regulatory restrictions. Liberates the east side to include some locations on the center of the city

Table 7.1Final model comparison and results

These models can help private companies such as Repsol, Iberdrola, GIC, EMT or the city council understand the best location for future charging stations as they are going to be needed in the future to continue the transition to a greener city where the electric vehicle will be a key factor in the transportation system.

7.2 FUTURE WORK

With a richer node base the model could perform better. The basic requirement to set a fast charging station is a secondary substation and usually there is one per two or three building blocks. Since that particular data is not available publicly the new grid could be arranged using the document '*DireccionesVigentes*_20200225' which contains the location and useful information from each building in the city and filtering even or odd numbers or multiples of five, a grid by blocks could be approximately build. On the other hand, the document has a downside the high number of nodes the grid would have, over 100000 nodes depending on the filtering. These many nodes make the document untreatable as MATLAB would take too long to process the data and more time doing the branch and bound and calculations for the models. Another possibility could be dividing the grid into districts to have 21 detailed grids. Developing the model for a grid of neighborhoods all around the city to afterwards set that limitation to a new model with the building block grids. For example, in the case of model 1.1, 4 new locations should be built on Centro's district(01) adding a new constrain to the grid by blocks that set the number of locations to 4.

Other useful data could include information regarding the actual demand of electric vehicles on the charging stations that already exist so the demand does not have to be estimated using the percentage of electric vehicles on the city but rather know the behavior of the driver, how much time do they spend charging on public stations?, what is their charging routine (while working, while shopping, no routine at all)? To solve these questions a survey was developed using Google Forms, however it had a small reach landing on very few electric vehicle owners who mostly did not charge on public charging stations making it not useful for the project.

Finally, since the construction, design and development of these projects take time it will be useful not only to use the present demand of fast charging stations but a prediction of the number of electric vehicles and its demand when the charging stations will be available.

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[ALIB20] Alibaba "Ev Charging 16A Type2 J1722 Iec62196-2 Male Ev07Ee-H Cable",2020.

[USDOE15] The U.S. Department of Energy "Costs Associated With Non-Residential Electric Vehicle Supply Equipment", 2015.

[DGT20] Dirección General de Tráfico. Infocar Map, 2020.

[MAD20] Madrid City Council. Puntos de Recarga de vehículos eléctricos de acceso público, 2020.

[MADDC20] Madrid City Council. Distritos en cifras. Statistics. 2020.

ANNEX A SUSTAINABLE DEVELOPMENT GOALS

Spain is taking new measurements to combat climate change and fulfill and ensure the Sustainable Development Goals. Following the knowledge platform of the United Nations, The Sustainable Development Goals (SDG) are 17 targets that the United Nations adopted for The 2030 Agenda for Sustainable Development in 2015. At its core, the purpose of these objectives sustains economic growth, social inclusion and environmental protection in a partnership and peaceful way. The 17 objectives focus on the improvement of poverty, hunger, health and well-being, education gender equality, clean water and sanitation, affordable clean energy, work and economic growth, industry, innovation and infrastructure, inequalities, sustainable cities and communities, responsible consumption and production, climate action, sustainability of oceans and terrestrial ecosystems, peace ,justice and partnership for the goals. On this study many goals will be tackled such as: 7.Affordable and Clean energy, 9.Industry, innovation, and infrastructure, 11.Sustainable cities and communities and 13. Climate Action. But amongst all of them a major part of the sustainable work will be centered on 13. Taking urgent action to combat climate change and its impacts.

Improvements will be made on target 13.2 Integrating climate change measures into national policies, strategies, and planning. To do so, some objectives that were proposed in Brussels by the Spanish government for 2030 include trying to reach 5 million of electric vehicles compared to the 45.000 we have today, decreasing by 30% CO2 transport emissions. Relating these policies with our topic, The European Commission and European Parliament has conservatively calculated that to fulfill these objectives Spain will need over 220.000 charging points by 2030 [PATIÑO18].

With an impact on the EV market more improvements will be made on target 13.A, on the table, a plan of investment of 1,000 Million Euros to help the electric vehicle between 2020 and 2025 as towards the UN $100 Billion climate change commitment.

The Spanish government is not only changing is monetary commitments but has also changed legislation. In October 2018, the Royal Decree-Law 15/2018 was passed and some of the modifications compared to the previous legislations were:

Suppression of the *Gestor de Carga* . This measurement means the liberalization of the charging station market. This figure made everyone who wanted to install a charging point in their establishment to register as a *Gestor de Energía* . From now on this legislation allows any establishment and business, including local governments, hotels, supermarkets, or users to install and sell energy directly to other drivers. This suppression makes the process of installing a charging point less tedious and more convenient. This new legislation also decreases the price of electricity for electric vehicle consumption.

As well as in other capitals and major cities, Spanish's transportation and mobility minister, Luis Ábalos, wants to invest on charging stations in Madrid presenting a royal decree-law to facilitate the implementation of electric vehicle charging stations with a similar treatment to today's gas stations [BLAZ20]. Another important legislation the government has wrote and the most restrictive so far, would be Plan A of Air Quality and Climate Change, in particular , *Madrid Central.*

Madrid Central Low Emission Zone (Information from the city council of Madrid) bounds a low emission zone that started to operate on November 30th,2018 [AYUNT18]. This measurement contained on the Plan A of Air Quality and Climate Change, favors the pedestrian, the bicycle and public transport, which gets more importance and space with the reconfiguration of streets like Gran Via or Atocha. The central district would act as lungs in the heart of the city. The area extends to 1166 acres and covers the 4 priority residential areas in the city: *Sol, Embajadores, Palacio* and *Cortes* as well as the districts of *Univerisdad* and *Justicia*. Likewise, there are restrictions to private and public vehicles. Each vehicle is assigned a label according to a vehicle's carbon emission and year of manufacture between 0, Eco, B or C going from less carbon emitter to more carbon emitter. The following measurements define the general regulation criteria for the districts mentioned before:

- Vehicles with a 0-emission environmental tag are able to move and park freely in any regulated parking zone operated by *SER*(*Servicio de Estacionamiento Regulado)* which regulates the parking service.
- Vehicles with ECO environmental tags are allowed to enter and park in *SER* designated zones during regular hours and not exceed a maximum of two hours.
- Vehicles with C or B environmental tag are allowed to enter under the circumstance that they park on a public parking, private garage, or not endowed areas. Not endowed

areas are classified for exclusive access for public organisms, embassies, sanitary centers, hotels, and extraordinary activities.

ANNEX B DISTRICTS AND NEIGHBORHOODS

District 01 *Centro*

Centro district located in the inner part of the city is formed by the following 6 neighborhoods:

11: *Palacio*

12: *Embajadores*

13: *Cortes*

14: *Justicia*

15: Universidad

16: *Sol*

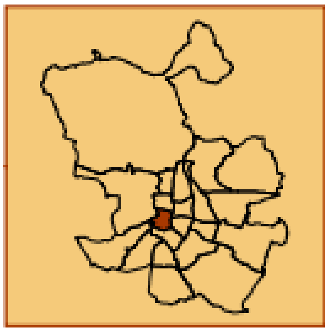

Figure B. 1 District Location. [MADDC20]

Figure B. 2 Neighborhood distribution. [MADDC20]

District 02 *Arganzuela*

Arganzuela is adjacent to *Centro* district and is formed by the following neighborhoods

21: *Imperial*

22: *Acacias*

23: *Chopera*

24: *Legazpi*

25: *Delicias*

26: *Palos de Moguer*

27: *Atocha*

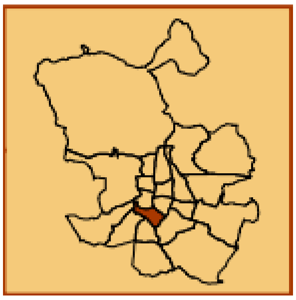

Figure B. 3 District Location. [MADDC20]

Figure B. 4 Neighborhood distribution. [MADDC20]

District 03 *Retiro*

Retiro's district is formed by the following neighborhoods

31: *Pacífico*

32: *Adelfas*

33: *Estrella*

34: *Ibiza*

35: *Jerónimos*

36: *Niño Jesús*

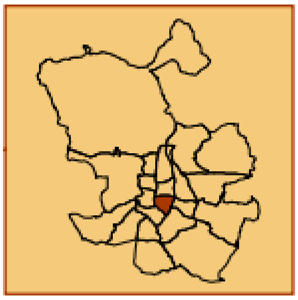

Figure B. 5 District Location. [MADDC20]

Figure B. 6 Neighborhood distribution. [MADDC20]

District 04 *Salamanca*

Salamanca district is formed by the following neighborhoods:

41: *Recoletos*

42: *Goya*

43: *Fuente del Berro*

44: *Guindalera*

45: *Lista*

46:*Castellana*

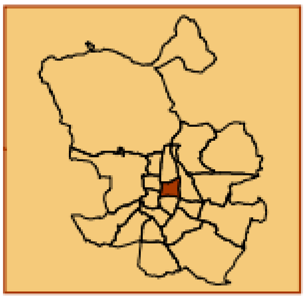

Figure B. 7 District Location. [MADDC20]

Figure B. 8 Neighborhood distribution. [MADDC20]

<u>District 05 *Chamartín*</u>

51: *El Viso*

52: *Prosperidad*

53: *Ciudad Jardín*

54: *Hispanoamérica*

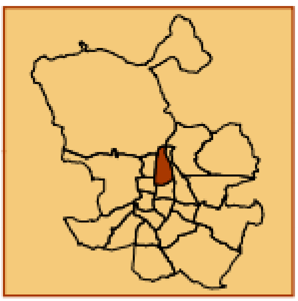

Figure B. 9 District Location. [MADDC20]

55: *Nueva España*

56: *Castilla*

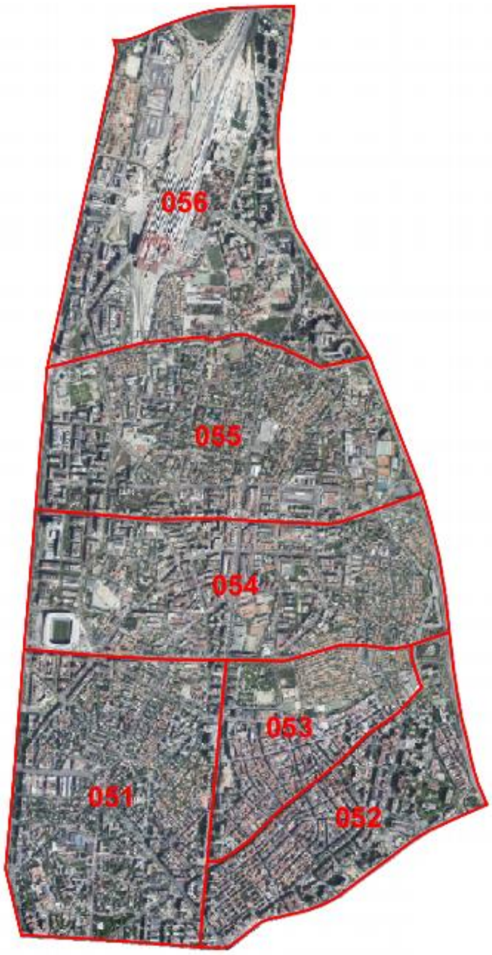

Figure B. 10 Neighborhood distribution. [MADDC20]

District 06 *Tetuán*

61: *Bellas Vistas*

62: *Cuatro Caminos*

63: *Castillejos*

64: *Almenara*

65: *Valdeaceras*

66: *Berruguete*

Figure B. 11 District Location. [MADDC20]

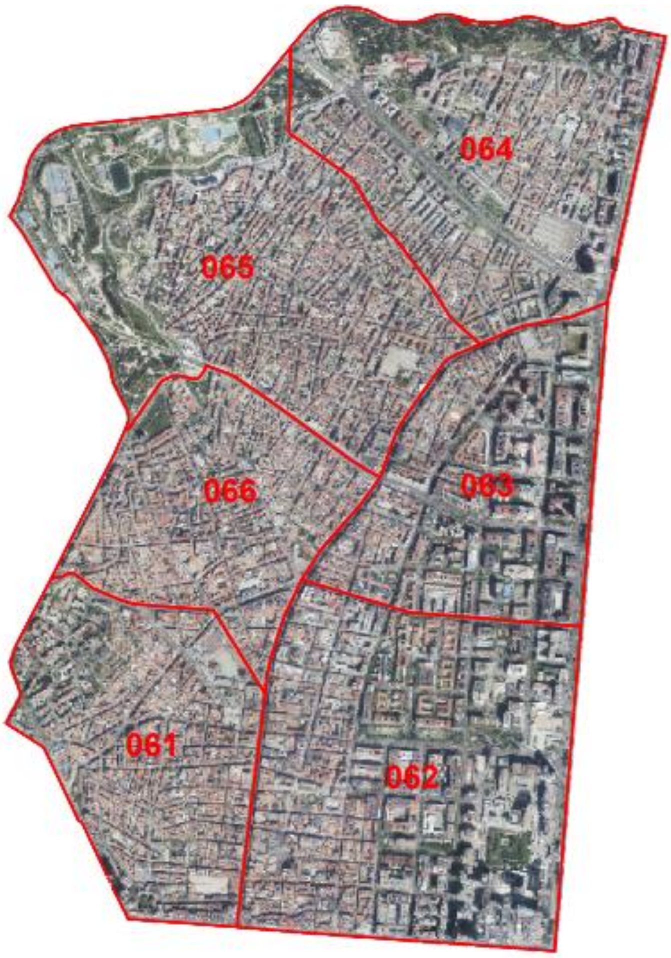

Figure B. 12 Neighborhood distribution. [MADDC20]

District 07 *Chamberí*

71: *Gaztambide*

72: *Arapiles*

73: *Trafalgar*

74: *Almagro*

75: *Ríos Rosas*

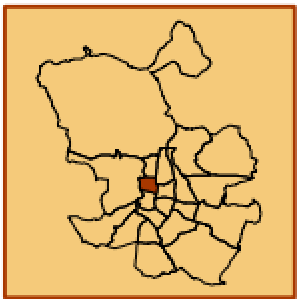

Figure B. 13 District Location. [MADDC20]

76: *Vallehermoso*

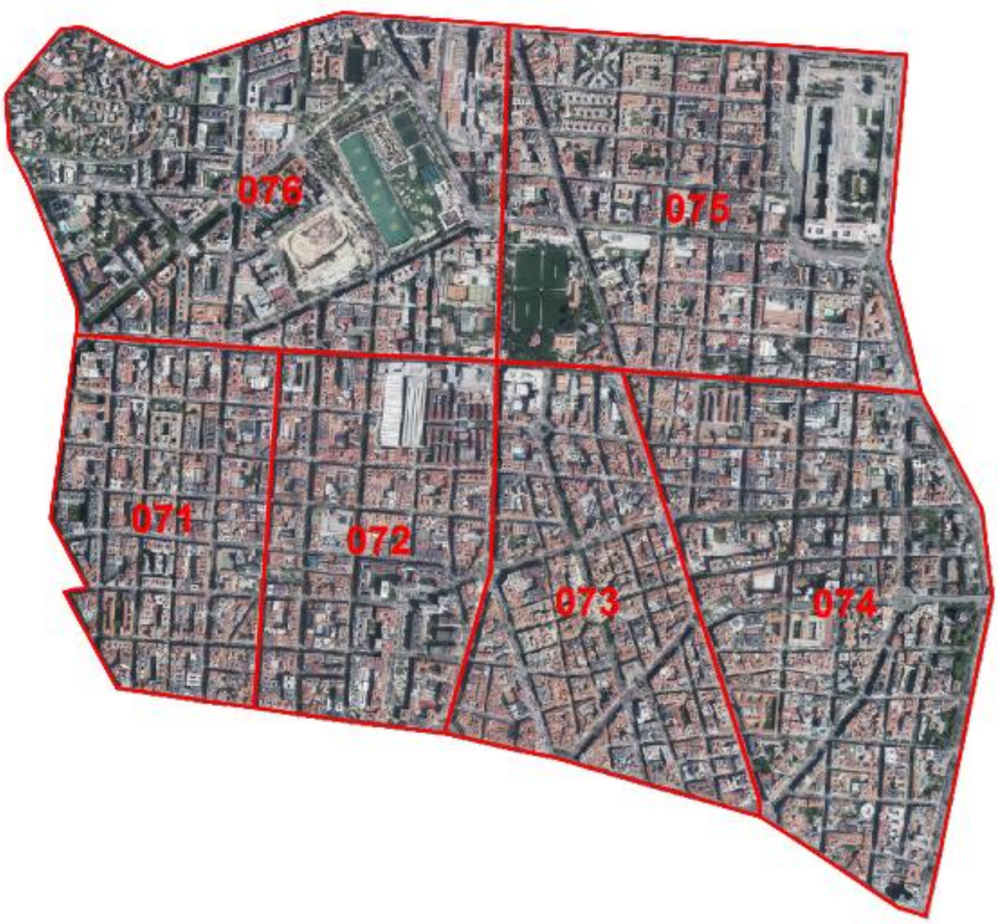

Figure B. 14 Neighborhood distribution. [MADDC20]

<u>District 08 *Fuencarral-El Pardo*</u>

Figure B. 15 District Location. [MADDC20]

81: *El Pardo*

82: *Fuertelarreina*

83: *Peñagrande*

84: *Pilar*

85: *La Paz*

86: *Valverde*

87: *Mirasierra*

88: *El Goloso*

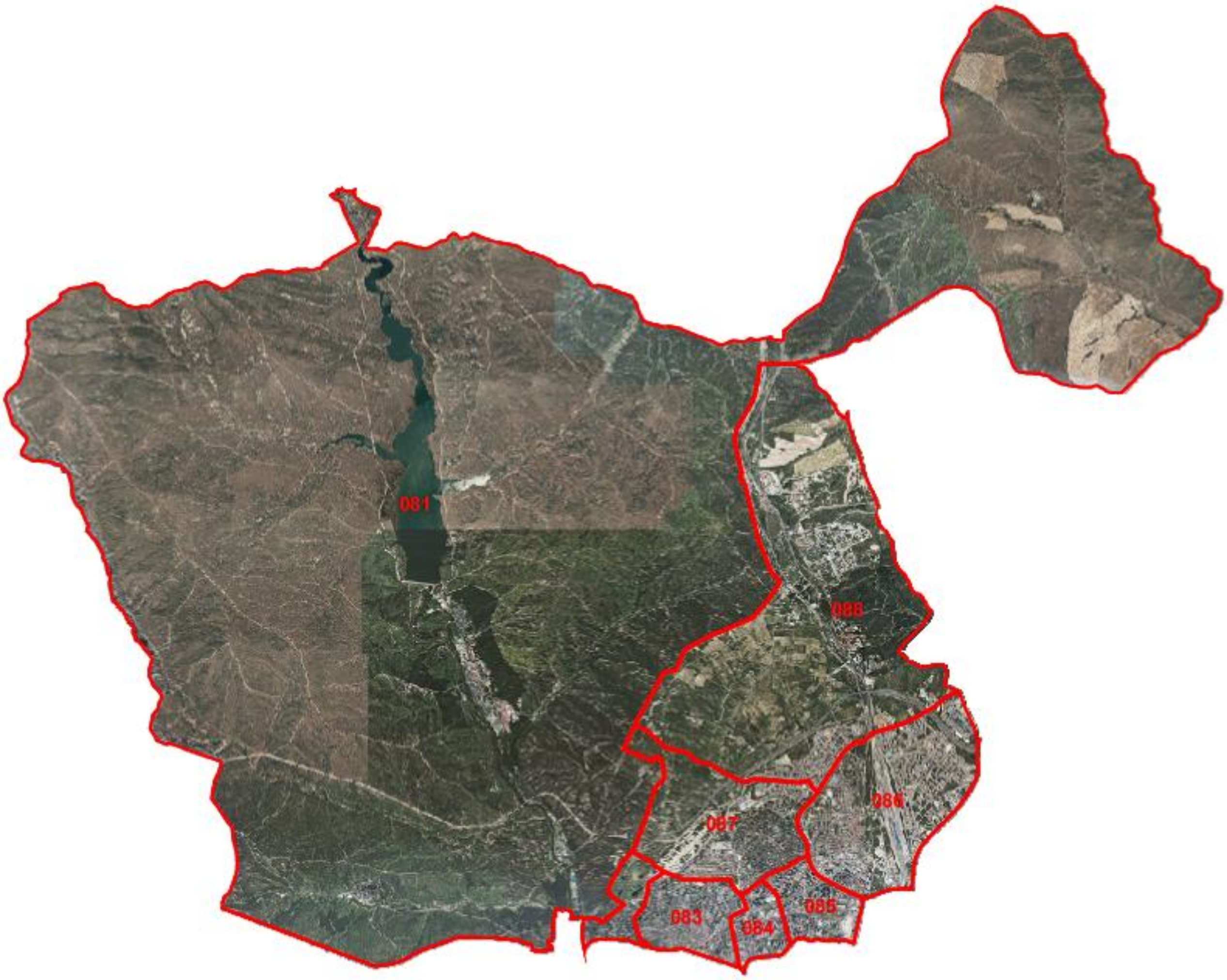

Figure B. 16 Neighborhood distribution. [MADDC20]

District 09 *Moncloa-Aravaca*

91: *Casa de Campo*

92: *Argüelles*

93: *Ciudad Universitaria*

94: *Valdezarza*

95: *Valdemarín*

96: *El Plantío*

97: *Aravaca*

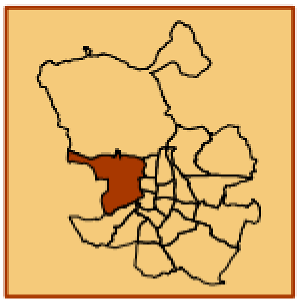

Figure B. 17 District Location. [MADDC20]

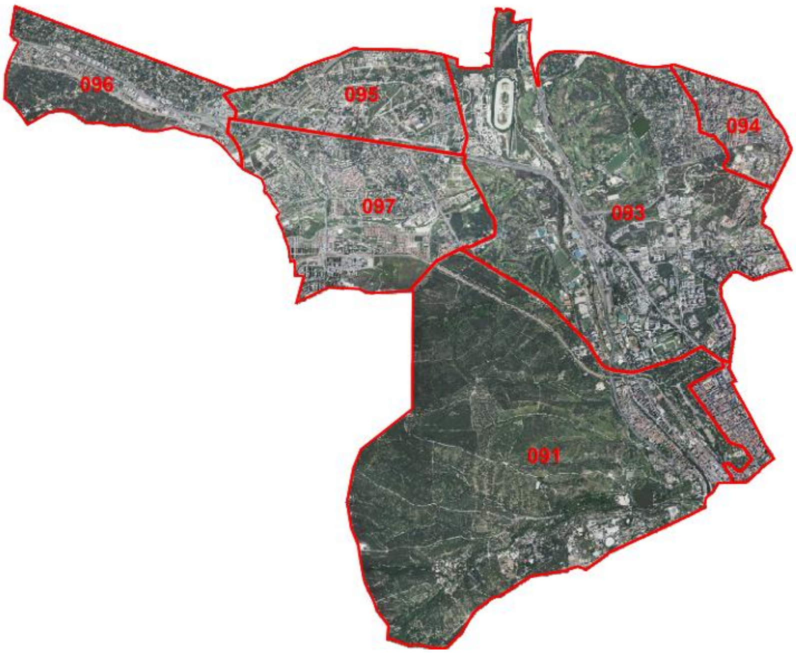

Figure B. 18 Neighborhood distribution. [MADDC20]

District 10 *Latina*

101: *Los Cármenes*

102: *Puerta del Ángel*

103: *Lucero*

104: *Aluche*

105: *Campamento*

106: *Cuatro Vientos*

107: *Las Águilas*

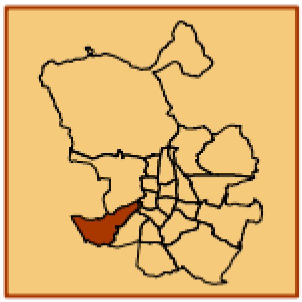

Figure B. 19 District Location. [MADDC20]

Figure B. 20 Neighborhood distribution. [MADDC20]

District 11 *Carabanchel*

111: *Comillas*

112: *Opañel*

113: *San Isidro*

114: *Vista Alegre*

115: *Puerta Bonita*

116: *Buena Vista*

117: *Abrantes*

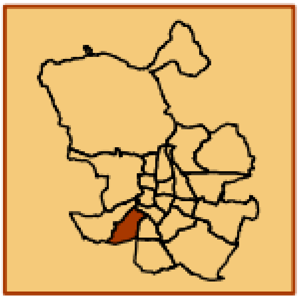

Figure B. 21 District Location. [MADDC20]

Figure B. 22 Neighborhood distribution. [MADDC20]

<u>District 12 *Usera*</u>

121: *Orcasitas*

122: *Orcasur*

123: *San Fermín*

124: *Almendrales*

125: *Moscardó*

126: *Zofio*

127: *Pradolongo*

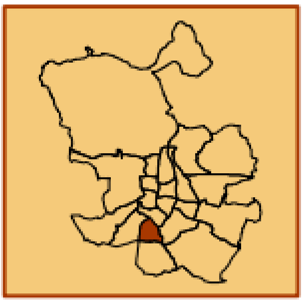

Figure B. 23 District Location. [MADDC20]

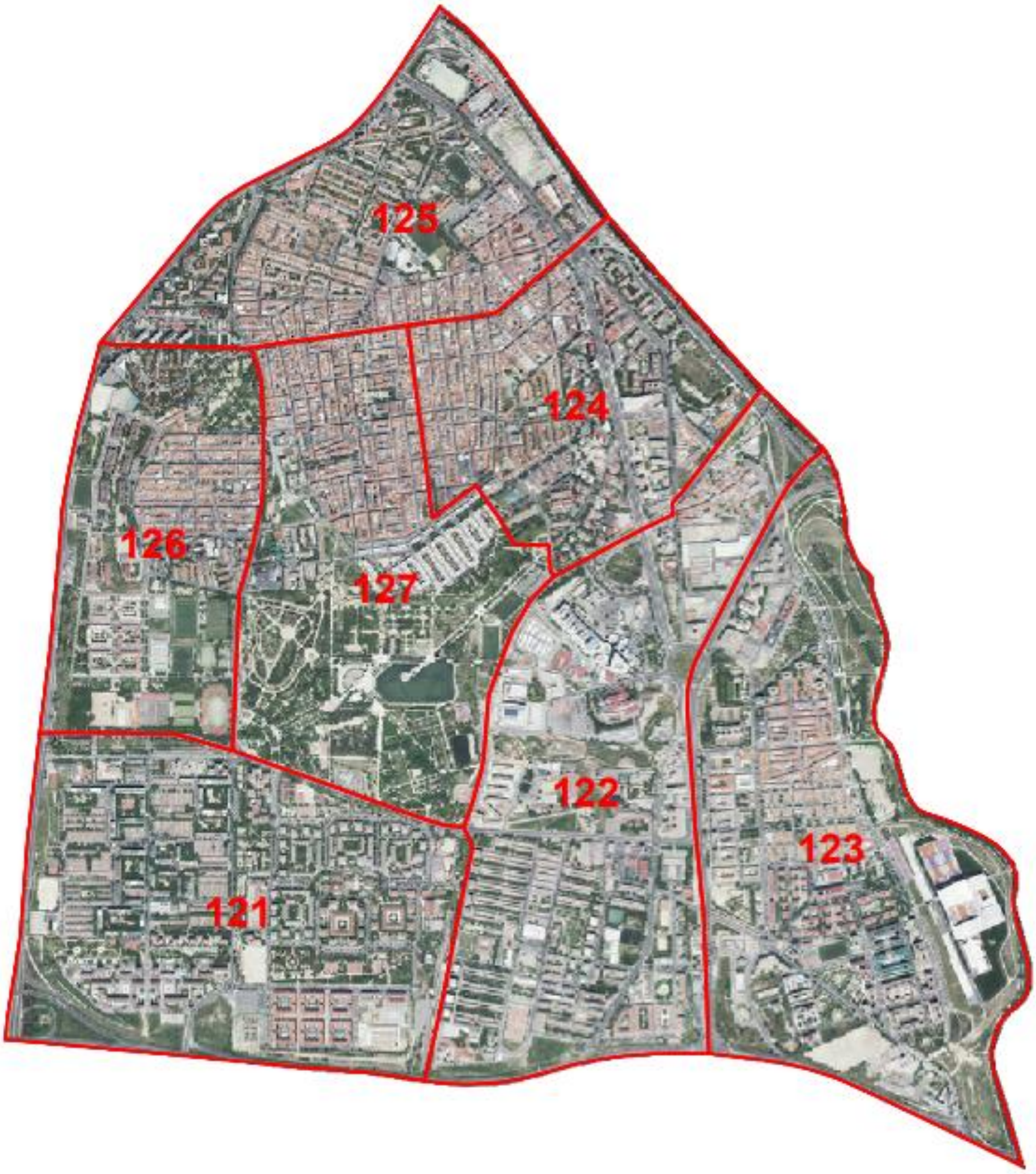

Figure B. 24 Neighborhood distribution. [MADDC20]

District 13 *Puente de Vallecas*

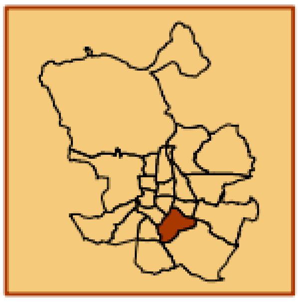

Figure B. 25 District Location. [MADDC20]

131: *Entrevías*

132: *San Diego*

133: *Palomeras Bajas*

134: *Palomeras Sureste*

135: *Portazgo*

136: *Numancia*

Figure B. 26 Neighborhood distribution. [MADDC20]

District 14 *Moratalaz*

141: *Pavones*

142: *Horcajo*

143: *Marroquina*

144: *Media Legua*

145: *Fontarrón*

146: *Vinateros*

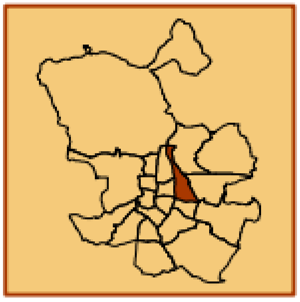

Figure B. 27 District Location. [MADDC20]

Figure B. 28 Neighborhood distribution. [MADDC20]

District 15 *Ciudad Lineal*

151: *Ventas*

152: *Pueblo Nuevo*

153: *Quintana*

154: *Concepción*

155: *San Pascual*

156: *San Juan Bautista*

157: *Colina*

158: *Atalaya*

159: *Costillares*

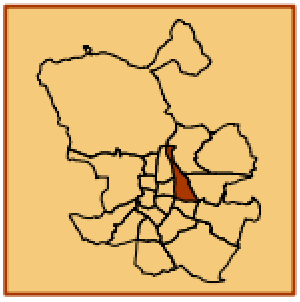

Figure B. 29 District Location. [MADDC20]

Figure B. 30 Neighborhood distribution. [MADDC20]

District 16 *Hortaleza*

161: *Palomas*

162: *Piovera*

163: *Canillas*

164: *Pinar del Rey*

165: *Apóstol Santiago*

166: *Valdefuentes*

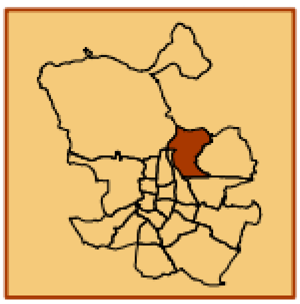

Figure B. 31 District Location. [MADDC20]

Figure B. 32 Neighborhood distribution. [MADDC20]

District 17 *Villaverde*

171: *Villaverde Alto, C.H. de Villaverde*

172: *San Cristóbal*

173: *Butarque*

174: *Los Rosales*

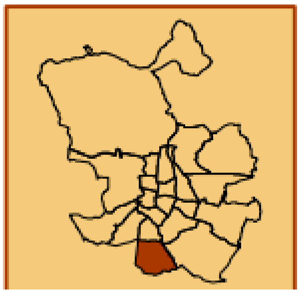

Figure B. 33 District Location. [MADDC20]

175: *Los Ángeles*

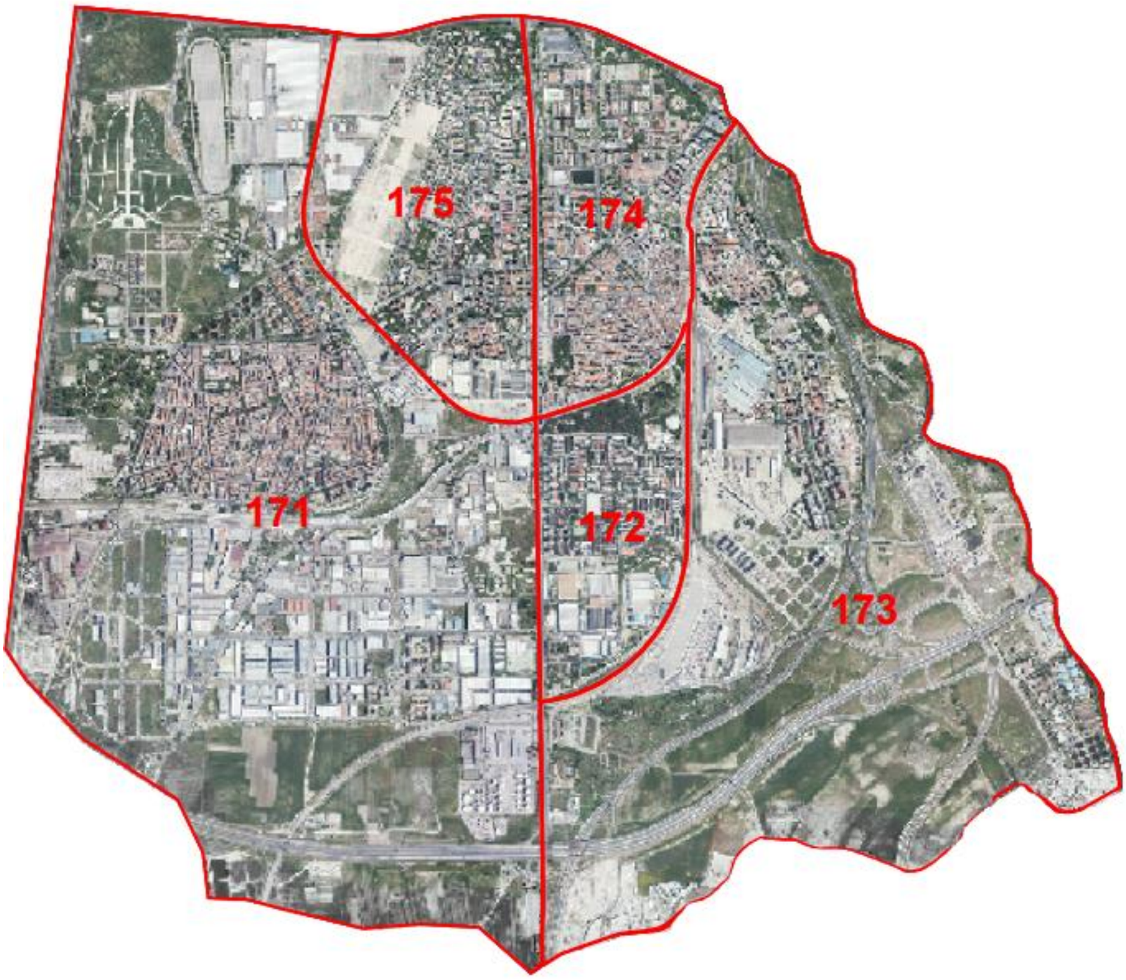

Figure B. 34 Neighborhood distribution. [MADDC20]

District 18 *Villa de Vallecas*

181: *Casco Histórico de Vallecas*

182: *Santa Eugenia*

183: *Ensanche de Vallecas*

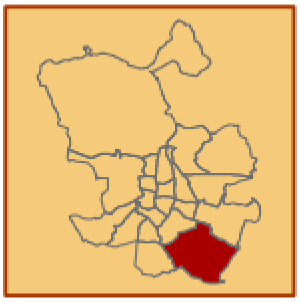

Figure B. 35 District Location. [MADDC20]

Figure B. 36 Neighborhood distribution. [MADDC20]

<u>District 19 *Vicálvaro*</u>

191: *Casco Histórico de Vicálvaro*

192: *Valdebernardo*

193: *Valderrivas*

194: *El Cañaveral*

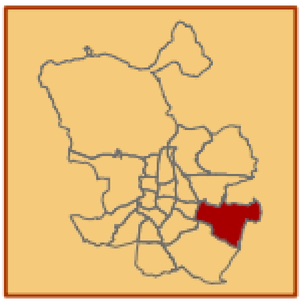

Figure B. 37 District Location. [MADDC20]

Figure B. 38 Neighborhood distribution. [MADDC20]

District 20 *San Blas-Canillejas*

201: *Simancas*

202: *Hellín*

203: *Amposta*

204: *Arcos*

205: *Rosas*

206: *Rejas*

207: *Canillejas*

208: *Salvador*

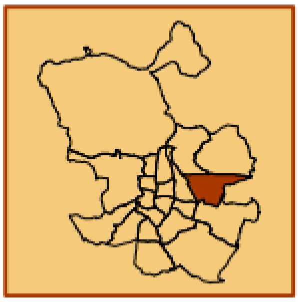

Figure B. 39 District Location. [MADDC20]

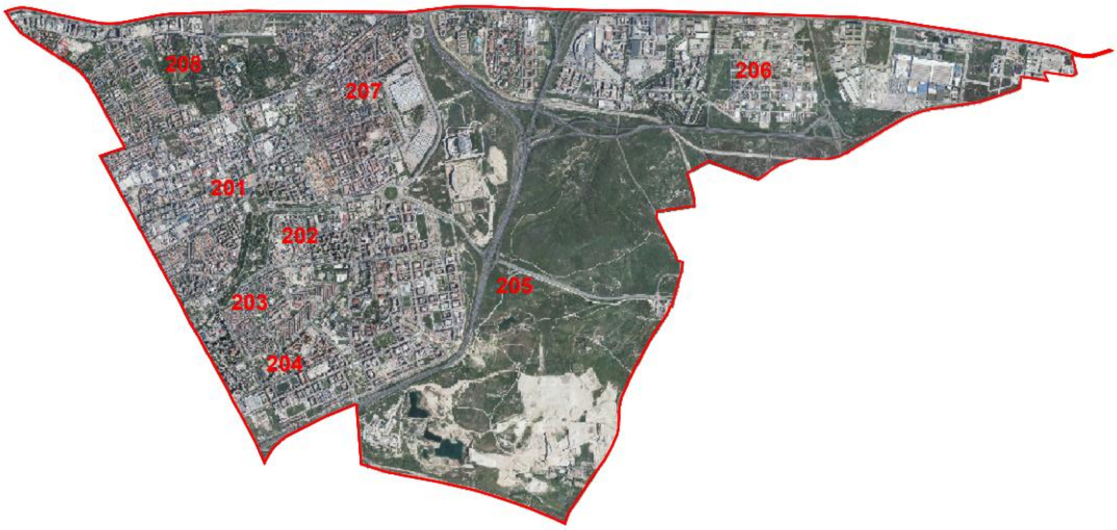

Figure B. 40 Neighborhood distribution. [MADDC20]

District 21 *Barajas*

211: *Alameda de Osuna*

212: *Aeropuerto*

213: *Casco Histórico de Barajas*

214: *Timón*

215: *Corralejos*

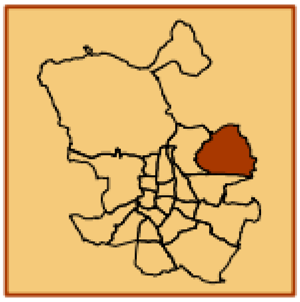

Figure B. 41 District Location. [MADDC20]

Figure B. 42 Neighborhood distribution. [MADDC20]

ANNEX C INCOMING TRAFFIC TO MADRID

A-6 Pk 3.5C: Located on the North West of the city.

Average traffic intensity: 5100Veh/h

Car percentage from all vehicles 100%

Time Frame	7-8 am	3pm	8pm
Number of vehicles	1750	4000	2750

Table C. 1 Daily peak traffic records A-6 Pk 3.5C [DGT20]

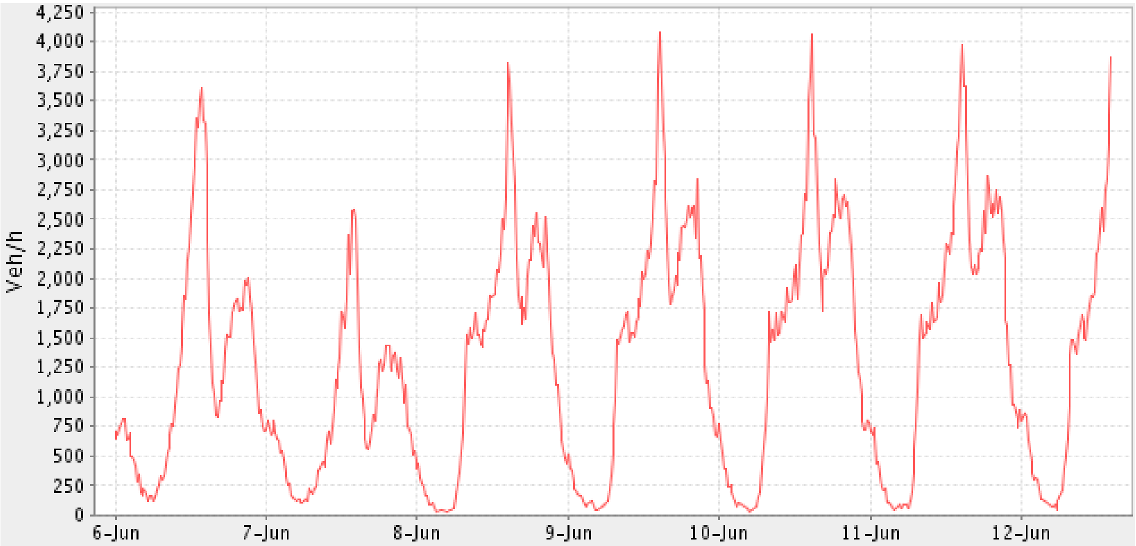

Figure C. 1 Weekly traffic intensity A-6 Pk 3.5C [DGT20]

Figure C. 2 Relative location of the information post on A-6 Pk 3.5C [DGT20]

A-5 Pk 10.69C: Located on the West side of the city.

Average traffic intensity: 5460 Veh/h

Car percentage from all vehicles 97%

Time Frame	7-8 am	3pm	8pm
Number of vehicles	3000	5000	4000

Table C. 2 Daily peak traffic records A-5 Pk 10.69C [DGT20]

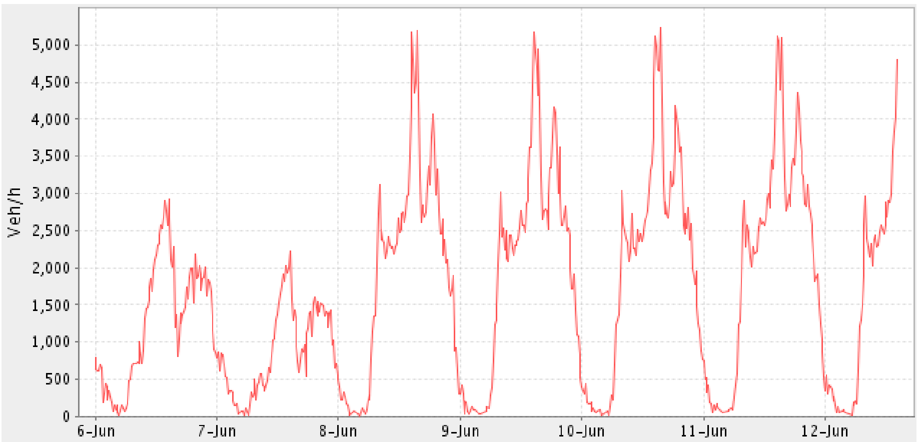

Figure C. 3 Weekly traffic intensity A-5 Pk 10.69C [DGT20]

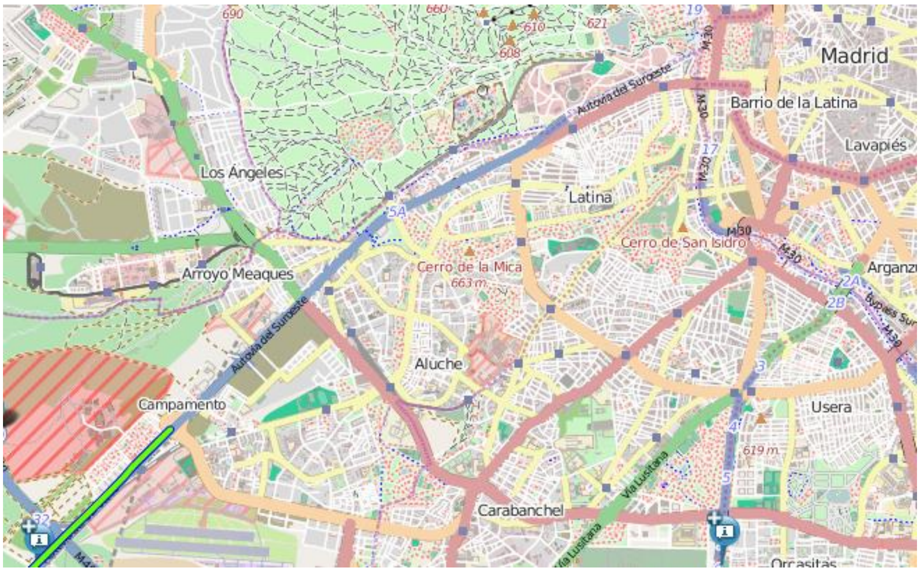

Figure C. 4 Relative location of the information post on A-5 Pk 10.69C [DGT20]

A-42 Pk 5.8C: Located on the South side of the city.

Average traffic intensity: 5220 Veh/h

Car percentage from all vehicles 100%

Time Frame	7-8 am	3pm	8pm
Number of vehicles	4500	5500	4500

Table C. 3 Daily peak traffic records A-42 Pk 5.8C [DGT20]

Figure C. 5 Relative location of the information post on A-42 Pk 5.8C [DGT20]

A-2 Pk 5.5 C: Located on the East side of the city.

Average traffic intensity: 4500Veh/h

Car percentage from all vehicles 97%

Time Frame	7-8 am	3pm	8pm
Number of vehicles	3250	3750	2750

Table C. 4 Daily peak traffic records A-2 Pk 5.5 C [DGT20]

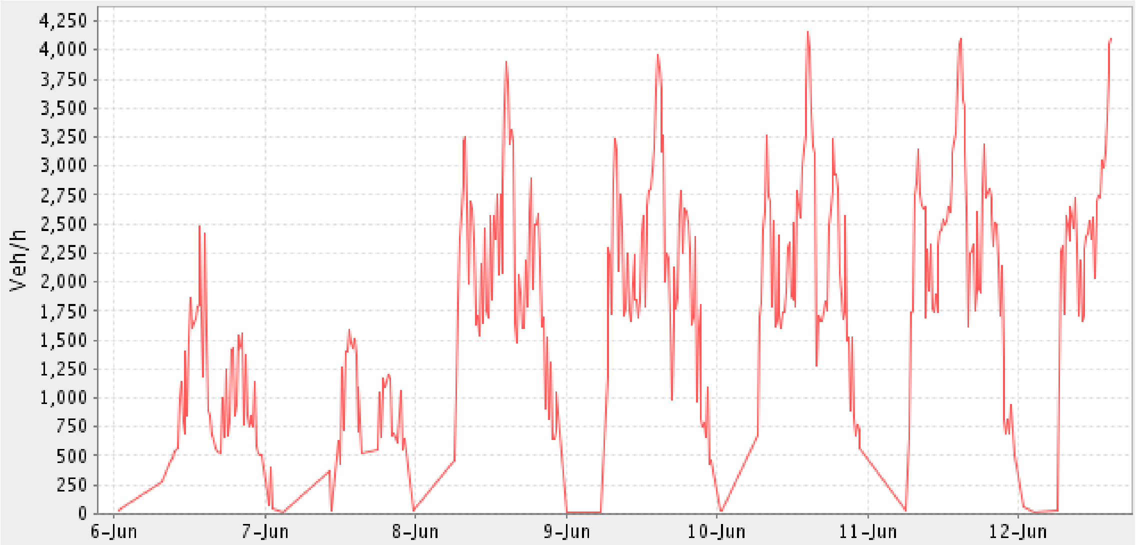

Figure C. 6 Weekly traffic intensity A-2 Pk 5.5 C [DGT20]

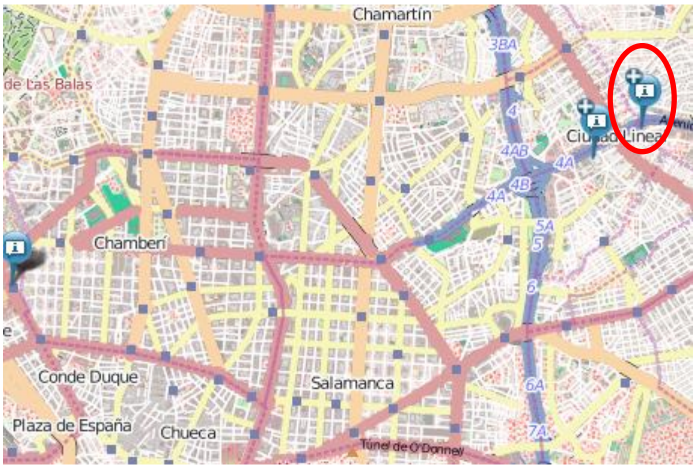

Figure C. 7 Relative location of the information post on A-2 Pk 5.5 C [DGT20]

M-40 Pk 5.45C: Located on the North East of the city

Average traffic intensity: 4260 Veh/h

Car percentage from all vehicles 96%

Time Frame	7-8 am	3pm	8pm
Number of vehicles	3500	4500	3650

Table C. 5 Daily peak traffic records M-40 Pk 5.45C [DGT20]

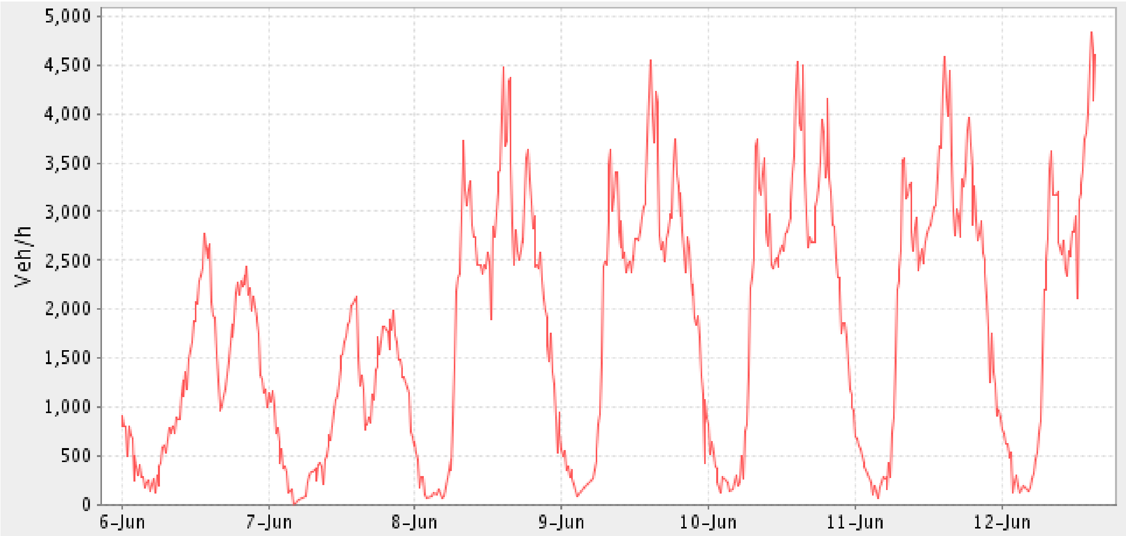

Figure C. 8 Weekly traffic intensity M-40 Pk 5.45C [DGT20]

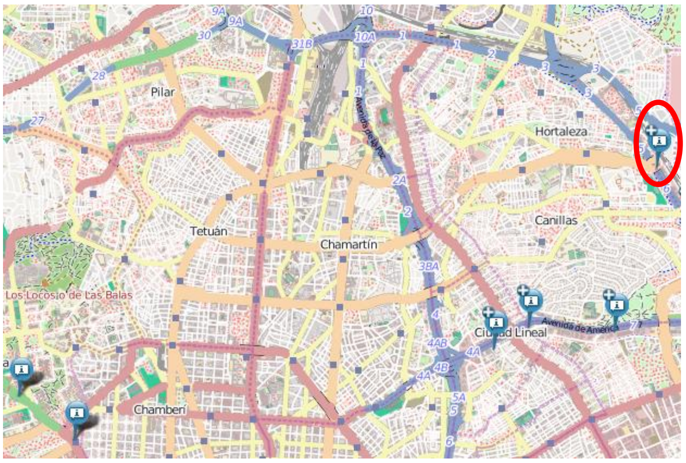

Figure C. 9 Relative location of the information post on M-40 Pk 5.45C [DGT20]