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Roundabouts and the Energy Consumption of Electrical Vehicles

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ABSTRACT
Understanding how the energy consumption of electrical vehicles behave on intersections can be paramount to save on electricity and reduce the emissions of greenhouse gases. This study uses a large dataset of high-frequency trajectory data to verify the feasibility of intersection analysis and study how roundabouts fare against each other when it comes to the energy consumption of EVs. The results show that there can be a difference of 25-33% in the consumption inside roundabouts depending on their category. They also show that the speed of the vehicles as they enter the roundabouts correlates to their energy consumption in a polynomial fashion.

CCS CONCEPTS
• Information systems → Geographic information systems.

KEYWORDS
Efficiency, EV, GPS, Intersection, OBD, Roundabout, Speed

1 INTRODUCTION
The electrification of vehicles is an undeniable global trend. Governments all around the world are pushing for electrical vehicles (EV) in lieu of internal combustion engine vehicles (ICEV). Whether through incentives for the purchase of new EVs or the banning on sales of new petrol and diesel cars, it is clear that the future of the transportation sector runs on electricity [4].

Although pure EVs do not emit any greenhouse gases (GHG) themselves, there is GHG emission on the generation and distribution of the electricity used to power them. The amount of CO₂ per kWh varies greatly from one country to another depending on its energy mix. For example, in 2019, for each kWh of electricity produced in the United States, 393 grams of CO₂ were released into the atmosphere, for EU-28, 306 grams, and for China, 560 grams [17]. Therefore, helping drivers reduce the energy spent driving also helps reducing GHG emissions.

In this study, we use a large dataset of high-frequency GPS-based trajectories to compare and analyze the energy consumption of EVs as they pass through roundabouts. Roundabouts are important elements of modern traffic infrastructure. Not only they show traits of eco-friendliness, such as less pavement devoted to roadways and lower vehicular fuel usage and emissions, they are also associated with enhancing the performance and safety of intersections [13].

Given the increasing popularity of both EVs and roundabouts, specially in Europe and the US [23][19], it becomes greatly important to understand how roundabouts interact with those vehicles.

With this paper, we contribute to the field of geographic information systems by using 1-Hz data to study intersections and verify its feasibility and to the field of computational transportation by offering novel and quantified information about energy consumption in roundabouts, how they fare against each other, and what factors play a role.

For this study, we use a dataset of 98,228 trajectories to compare and analyze 1,186 roundabouts in Denmark. The data comes from vehicles with permanently-installed GPS and OBD devices. The GPS device is responsible for the spatiotemporal aspect of the data and the OBD, for the instantaneous speed and power of the engine, allowing us to derive the energy consumption of the vehicle throughout a whole trajectory.

Even though there is substantial literature about roundabouts, the majority focus on the safety aspects or environmental impacts. Most of the literature that tackles the emissions aspect, do it by comparing roundabouts with signalized intersection or use a small number of different roundabouts. Also, most of those studies are for ICEVs. This leaves the study of energy consumption between different roundabouts underrepresented, specially for EVs [8]. To the best of our knowledge, this is the first study to compare roundabouts on a large scale and how they impact the energy consumption of EVs.

The remainder of the paper is organized as follows. Section 2 presents the related work. Section 3 describes roundabouts, their layouts and features. Sections 4 and 5 discuss the data foundation and the data analysis, respectively. Finally, Section 6 concludes the paper.
2 RELATED WORK

The combined use of GPS and OBD data for trajectory analysis is not new. It has been used in many different studies before, such as fuel consumption of hybrid vehicles [26], driving behaviour and traffic safety [25], and insurance management [28], establishing itself as a reliable and rich source of information.

GPS and OBD data is used in [7] to compare and analyze the differences in emissions between conventional and turbo roundabouts. The authors selected two sets of three roundabouts for each type and used vehicle specific power (VSP) to estimate the emissions. The results showed that turbo roundabouts yield 15% to 22% more than conventional roundabouts.

The authors of [21] also used GPS and OBD data and VSP to analyze emissions in roundabouts. The focus of the study was multilane roundabouts, more specifically the differences in emissions of vehicles as they use either the left or the right lane. The results showed that the emissions of the vehicles traveling in the right lane were 21% to 43% higher than the ones traveling in the left lane.

In [3], the authors proposed a method to compare the amount of pollutant emissions generated in roundabouts and signalized intersections given multiple input, such as demand, capacity, section length, and signal timing. The results showed that at low demand-to-capacity ratio, emission rates are higher at signalized intersections, but as demand approaches capacity, roundabouts tend to have higher emission rates.

Regarding vehicle throughput capacities of roundabouts, [27] examined the state-of-art in roundabout capacity modelling. The authors analyzed and compared three models: fully-empirical, gap acceptance, and simulation. The results showed that, although no model can fully explain the highly complex processes at roundabout, they can reasonably estimate the capacity. Also, the study revealed how much the behaviours of the drivers can affect the performance of the roundabouts.

In [24], the authors performed a thorough study on the performance of both conventional and modern roundabouts. The study focused on right-turn bypass lanes controlled by stop, yield, or free-flow signs and how they can improve the capacity and the emissions of roundabouts. Also, the authors did a cost analysis of how much fuel the improvements can save on an annual basis.

On a different take, the authors of [6] focused on the environmental aspects to develop a tool to assess the noise emission of both roundabouts and signalized intersection. Results showed that roundabouts are less noisy on average, but heavy vehicles can generate high-congestion situations, making them more noisy than signalized intersection for short periods of time.

In [18], the authors analyzed the safety aspect of 23 signalized intersections that were converted to roundabouts in the US. The study analyzed crash data and traffic volume from before and after the roundabouts were built. The results showed that the roundabouts reduced the number of crash severities and crash injuries by 40% and 80%, respectively.

Also on the safety aspect, the authors of [11] investigated crash data for roundabouts in order to identify factors of influence in South Korea. The authors used crash, speed, and geometry data from 14 roundabouts. The results indicated that most crashes were due to vehicles slowing down substantially before the intersection.

3 ROUNDABOUTS

A roundabout is a form of circular intersection (or junction) in which road traffic flows in a circular direction, around a central island, and the priority is given to the traffic already inside it. Roundabouts are designed to allow traffic to flow without idling, as opposed to signalized intersections, while increasing the overall safety of the intersection.

Over the last 60 years, roundabouts and the rules surrounding them evolved tremendously. Currently, modern roundabouts are considered to be safer for drivers, bikers, and pedestrians, more environmentally friendly, and cheaper, both to build and maintain, than signalized intersections.

As roundabouts can be quite different from one to another, we find important to establish some parameters to fairly compare them. In this paper, we look at two physical aspects of the roundabouts, which are the ones we have information about: the radius of the roundabout and the number of roads connected to it. There are, of course, many other aspects that are of interest in any study about roundabouts, specially regarding energy consumption, such as the number of lanes inside them or its road grade (also known as slope). These are not in the scope of this study.

The radius of a roundabout is derived from their circumference. We take the circumference as the sum of the length of the segments which road traffic flows in a circular direction, around a central island, and the priority is given to the traffic already inside it. Roundabouts are designed to allow traffic to flow without idling, as opposed to signalized intersections, while increasing the overall safety of the intersection.

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Figure 1: A roundabout in OpenStreetMap and its attributes.
The number of roads, also referred to as number of arms, is exactly the number of road segments connected to a roundabout. In this study, we count the number of arms by counting the number of road segments that either end or start at a roundabout. Again, we use OpenStreetMap for that. It is important to note that road segments can be unidirectional or bidirectional. We make no distinction in that regard when counting the number of arms. For example, the roundabout in Figure 1 have eight arms. But, if the roads were merged and bidirectional, it would be have four arms instead.

Later in the paper, we talk about the exit arm, which refers to the road the driver used to exit the roundabout. The exit arm is counted counterclockwise as the $n_{th}$ possible road that the driver can take after they enter the roundabout. Consider Figure 1 for an example. If a vehicle enters the roundabout via Bredgade (west) and exit the roundabout via Silkeborgvej (east), then we count that as exiting at the second arm.

4 DATA FOUNDATION

In this section, we present and discuss GPS and OBD data, the road network, trajectory data, and how we compute the energy consumption. We present the data statistics at the end of section.

4.1 GPS and OBD Data

A GPS (Global Positioning System) [9] is a spatiotemporal device capable of describing an object’s location in time by using latitude and longitude coordinates. This way, GPS data can be seen as the tuple $⟨lat, lon, ts⟩$.

The OBD (On-Board Diagnostics) [12] is a system that aggregates information from all the sensors in a vehicle, such as the instantaneous speed and the instantaneous engine power.

In this study, we combine both data sources into what we call GPS+ data. We synchronize samples from the same instant into a GPS+ point, that can be seen as the tuple $⟨gid, lat, lon, ts, spe, pow⟩$, in which $gid$ is the id of the point, $lat$ and $lon$, the latitude and longitude coordinates, $ts$, the timestamp, $spe$, the instantaneous speed of the vehicle, and $pow$, the instantaneous power of the engine. The value of $gid$ is created during synchronization, $lat$, $lon$, and $ts$, comes from the GPS data, and $spe$ and $pow$, from the OBD data.

4.2 Road Network

The road network is a directed graph $G(V, E)$, with $V$ as the set of vertices, $E$ as the set of edges, and $E \subseteq \{(x, y) \mid (x, y) \in V^2 \text{ and } x \neq y\}$. In this case, road segments are edges and vertices are intersections. This way, a road segment is a continuous segment of road between two intersections.

We use the open-source geographic database OpenStreetMap [15] and the Hidden Markov algorithm to match the GPS+ data to a road segment [14]. We process the points sequentially for each vehicle data history. We end a trajectory and start a new one whenever there is a gap of at least 180 seconds between two consecutive GPS+ points.

As the points are map-matched to road segments, a trajectory can be seen as a sequence of moves through road segments. Said moves are called subtrajectories. This way, a trajectory is a sequence of subtrajectories, and each subtrajectory can be seen as the tuple $(tid, sid, vid, rsid, G)$, in which $tid$ is the id of the trajectory, $sid$, the id of the subtrajectory, $vid$, the id of the vehicle, $rsid$, the id of the road segment, and $G$, the set of GPS+ points.

Figure 2 shows a sequence of map-matched GPS+ points (and its attributes) as a vehicle passes through a roundabout. In this particular example, the vehicle is traveling from west to east.

![Figure 2: The GPS+ points of a vehicle passing through a roundabout.](image)

4.3 Energy Consumption

We calculate the energy consumption of a trajectory (or any subsequence of it) as the amount of energy (in Wh) required to travel one kilometer. We calculate the power transferred from (or to) the battery between two consecutive points by taking the average power $pow$ between those points. We calculate the time $t$ between the points by taking the difference in their timestamps $ts$. And we calculate the distance $d$ between the points by using their latitude $lat$ and longitude $lon$. This way, the energy consumption $e$ between two consecutive points is:

$$e_{j,k} = \frac{pow_{j,k} \cdot t_{j,k}}{d_{j,k}}$$

We calculate the energy consumption for any sequence of points as the average of the energy consumption between all two consecutive points. We use a simple average as the time difference between any two points is fixed at 1 Hz (otherwise, we would have used a weighted average). Therefore, for any sequence of GPS+ points $G$, its energy consumption $E$ is calculated as follows:
As the focus of this study is the impact of the roundabouts in the energy consumption of the vehicles as they pass through the intersections, we only apply the calculations described above for the GPS+ points that are matched to a road segment classified as a roundabout. This way, whenever we talk about energy consumption, we mean inside the roundabout only. Consider Figure 2 for an example. There is a total of 17 GPS+ points in the figure. The first five points are matched to the road segment before the roundabout, while the last four points are matched to the road segment after it. The other eight points are matched to the roundabout and those are the ones we use to compute the energy consumption of the pass.

Finally, it is important to note that EVs are capable of recovering some of their kinetic energy back when they brake \[22\]. This is called regenerative braking, and it is represented by a negative power \( \text{pow} \), which can lead to a negative energy consumption \( E \). We do not make any evaluation regarding regenerative braking. In fact, we discard trajectories with negative energy consumption from our dataset as it isn’t in the scope of this study.

### 4.4 Data Statistics

For this study, we use 177 vehicles (35 Citroën C-Zero, 63 Mitsubishi iMiEv, and 79 Peugeot Ion) with permanently-installed GPS and OBD devices. We collect a total of 218,451 GPS+ points, between January 2012 and May 2014. From this data, we build 275,994 trajectories.

One of goals of this study is to verify whether 1-Hz data can be used for the study of intersections, specially roundabouts, so we need GPS data to be matched to the road segments classified as such. If the sampling rate of the GPS device is too slow, vehicles can go through the intersection without registering any GPS point on it (or at most, just a few). We start by assessing the quality of the data in this regard. Although there’s no specific metric for it, we start by looking at the number of passes through a roundabout that didn’t register any GPS+ point on it. Out of a total of 198,534 passes, 3,260 didn’t register any GPS+ point on the road segments of the roundabouts during map-matching, or 1.6%. A closer inspection of those passes indicates that the vast majority of them happened because the GPS device lost satellite coverage for some time and the vehicle passed through the roundabout during that time.

Another interesting metric is the number of GPS+ points matched to the roundabouts. The more points we have inside the roundabout, the more accurate is any assessment about what happens at it. Table 1 shows the number of GPS+ points matched to a roundabout, the number of passes we have with said number of points, and their percentage.

The data is well distributed. 97% of the passes have at least two points matched to the roundabouts and 51% have at least six points. Combined with the low number of passes that didn’t match any GPS+ points to the roundabouts, it shows that our 1-Hz data is of high quality and is well-suited for intersection analysis.

Now, we start to cleanse and process the data. As we use sensors to collect the data, it is reasonable to expect failures. Therefore, we cleanse the dataset to remove the trajectories for which there is missing or invalid data. In this case, we remove all the trajectories that have any GPS+ point missing the instantaneous power \( \text{pow} \), the speed \( \text{spe} \), or the timestamp \( \text{ts} \), as well as the points with instantaneous power \( \text{pow} \) lesser than -16,660 W or greater than 50,000 W (respective minimum and maximum possible power for the vehicles in the study). We also remove the trajectories that have any two consecutive points with a time difference greater than one second, which can happen when the GPS device loses satellite coverage.

We use OpenStreetMap (see Section 4.2) to identify the roundabouts and we remove the trajectories that do not pass through one. After all the cleansing we have 101,271 trajectories, that together passed through 1,232 different roundabouts, for a total of 198,534 passes.

As previously mentioned in Section 3, the radius of the roundabouts is a variable of interest. For an initial assessment, we divide the total pool of roundabouts in six percentiles based on their radius. Table 2 shows the intervals of radius, the total number of roundabouts for each, the number of segments of which we have data for, and the number of passes.

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of roundabouts for each, the number of segments of which we have data for, and the number of passes. We remove the data for the roundabouts with 1, 2, 9, 10, and 11 arms as we have a low number of passes for each (together, they amount for 2% of the data).

<table>
<thead>
<tr>
<th>Number of arms</th>
<th>Roundabouts</th>
<th>Data</th>
<th>Passes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>27</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>54</td>
<td>13</td>
<td>426</td>
</tr>
<tr>
<td>3</td>
<td>277</td>
<td>185</td>
<td>24,898</td>
</tr>
<tr>
<td>4</td>
<td>776</td>
<td>591</td>
<td>85,792</td>
</tr>
<tr>
<td>5</td>
<td>174</td>
<td>140</td>
<td>37,161</td>
</tr>
<tr>
<td>6</td>
<td>154</td>
<td>125</td>
<td>20,037</td>
</tr>
<tr>
<td>7</td>
<td>53</td>
<td>43</td>
<td>6,510</td>
</tr>
<tr>
<td>8</td>
<td>136</td>
<td>104</td>
<td>19,879</td>
</tr>
<tr>
<td>9</td>
<td>12</td>
<td>9</td>
<td>1,909</td>
</tr>
<tr>
<td>10</td>
<td>7</td>
<td>6</td>
<td>992</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>1</td>
<td>661</td>
</tr>
</tbody>
</table>

Table 3: Roundabouts by number of arms.

Also, in this study, we compare and analyze roundabouts based on their classification according to OpenStreetMap [16]. Each road, street, or path is classified according to their importance in a country’s system. Table 4 shows the categories, the total number of roundabouts for each, the number of segments of which we have data for, and the number of passes. We remove all the data for the tertiary link, secondary link, living street, and service categories from our analysis. For the former three, we have only a smidgen of data, and for the latter, a closer inspection showed that most of the service roundabouts are inside private or commercial properties, such as airports or parking lots. It is important to note that the classification we use here comes directly from OpenStreetMap and it is of the roundabouts themselves, not of the roads connected to them.

<table>
<thead>
<tr>
<th>Category</th>
<th>Roundabouts</th>
<th>Data</th>
<th>Passes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trunk</td>
<td>109</td>
<td>17</td>
<td>8,403</td>
</tr>
<tr>
<td>Primary</td>
<td>1,508</td>
<td>270</td>
<td>61,552</td>
</tr>
<tr>
<td>Secondary</td>
<td>2,171</td>
<td>408</td>
<td>78,023</td>
</tr>
<tr>
<td>Tertiary</td>
<td>2,655</td>
<td>538</td>
<td>97,552</td>
</tr>
<tr>
<td>Unclassified</td>
<td>597</td>
<td>147</td>
<td>12,794</td>
</tr>
<tr>
<td>Residential</td>
<td>1,033</td>
<td>258</td>
<td>9,596</td>
</tr>
<tr>
<td>Tertiary Link</td>
<td>4</td>
<td>1</td>
<td>42</td>
</tr>
<tr>
<td>Secondary Link</td>
<td>13</td>
<td>3</td>
<td>75</td>
</tr>
<tr>
<td>Living Street</td>
<td>10</td>
<td>2</td>
<td>21</td>
</tr>
<tr>
<td>Service</td>
<td>86</td>
<td>27</td>
<td>466</td>
</tr>
</tbody>
</table>

Table 4: Roundabouts by category.

Finally, as we are interested in the energy consumption inside the roundabouts, in order to make sure we have the most accurate data possible in this regard, we remove all the trajectories that have negative consumption (regeneration) inside the roundabout or have any GPS+ point in which the speed is equal or less than 2 km/h (2.7% of the total data). These cases indicate braking, which ideally happens before the roundabout, not inside it. The idea is to remove data in which the map matching algorithm didn’t perform so well.

After all the cleansing and processing, we have 98,228 trajectories, that together passed through 1,186 different roundabouts, for a total of 188,897 passes. These are unprecedented numbers in the literature of roundabouts, energy consumption, and EVs combined.

5 DATA ANALYSIS

In this study, the most important aspect of interest is the energy consumption inside the roundabouts. The goal is to analyze how different roundabouts perform in this regard. We use three metrics to group the roundabouts: radius, number of arms, and category. We also analyze the performance of the roundabouts during the day, the week, and the year. And we close the study with an analysis of how the speed of the vehicles change as they approach and exit the roundabouts and how that impacts the energy consumption.

5.1 Radius, Number of Arms, and Category

We start by looking at the energy consumption for different radius intervals. We are interested in checking if this simple aspect have any impact on the energy consumption and, if so, how much. Whenever we talk about radius, we use the intervals from Table 2. Figure 3 shows the energy consumption per roundabout radius interval.

![Figure 3: Energy consumption per roundabout radius interval.](image)

The figure shows that roundabouts with a shorter radius have, on average, a higher energy consumption than roundabouts with a larger radius. For the first interval, the average is 323 Wh/km, while for the last one, it is 210 Wh/km, or 35% less.

Our initial assessment of the data tells us that the larger the roundabout, the more arms it has, on average. So, we do the same analysis, but we use the number of arms to group the roundabouts. Figure 4 shows the energy consumption per roundabout number of arms.
Figure 4: Energy consumption per roundabout number of arms.

Figure 4 shows a similar pattern than Figure 3. Roundabouts with less arms have a worst performance when it comes to energy consumption compared to roundabouts with more arms. For roundabouts with 3 arms, the average is 251 Wh/km, while for roundabouts with 8 arms, it is 208 Wh/km, or 21% less. If we consider the average for roundabouts with 4 arms as the higher average instead, 260 Wh/km, it becomes 25% less.

Finally, we use the category of the roundabouts as variable of interest. The categories come from OpenStreetMap and they are: residential (RES), unclassified (UNC), tertiary (TER), secondary (SEC), primary (PRI), and trunk (TRU). This sequence is not arbitrary. Moving from residential roads to trunks in this way increases the importance of the roads in the country’s system. Figure 5 shows the energy consumption for each category.

Figure 5: Energy consumption per roundabout category.

Once again, we see the same pattern. As we go from residential to trunk roundabouts, overall, both the radius and the number of arms increase. While residential roundabouts have an average radius of 12.7 meters and an average of 3.9 arms, trunk roundabouts have an average radius of 33.5 meters and an average of 5.9 arms.

This doesn’t mean that all residential roundabouts are small and have a low number of arms or that large roundabouts with many arms are all trunks, and certainly there are other aspects that differentiate them, but it does show there’s an intimate relation between the three and that, when it comes to roundabouts, the category encompasses the radius and the number of arms to an extend.

Another aspect that we take interest into is the arm that the driver used to exit the roundabout. The 1st arm means that the driver exited the roundabout using the first possible road (counted in the counterclockwise direction starting from the road they used to enter the roundabout). Figure 7 shows the energy consumption per exit arm.

Figure 7: Energy consumption per exit arm.

Overall, the 1st exit has an average of 329 Wh/km, while the 2nd, 3rd, and 4th exits have averages of 233, 216, and 207 Wh/km, respectively, or 29-37% less. This is an interesting and surprising result. To make sure it repeats itself across different types of roundabouts, we use the category to group them. Figure 8 shows the average energy consumption per exit arm per roundabout category.
Once again, the 1st exit has a worst energy consumption that the other three exits. The average energy consumption for the 1st exit is 362 Wh/km, while for 2nd, 3rd, and 4th, they are 263, 250, 227 Wh/km, respectively, 27-37% less.

Using a different arm to exit the roundabout is not really an option. But, for roundabouts where there is too much traffic exiting at a first arm after an specific entry road, the results support the study and evaluation of possibly building shortcuts to connect these roads in order for this specific traffic to avoid the roundabout.

5.2 Seasonality

The data we use in this study spans over 29 months, from January 2012 to May 2014. This allow us to explore if there is any seasonal effect. We look at the day, week, and year. Instead of grouping the roundabouts by radius, number of arms, or category, we use only the category as a variable of interest as previous results showed that it accounts for the others. Figure 9 shows the average energy consumption per hour of the day per roundabout category. We disregard the data from 0:00 to 5:59 as there are few passes during this time.

As expected, the figure shows an overall increase in the consumption between 6:00 and 8:00, as well as between 15:00 and 17:00, for all categories. These are the typical hours which people go to and get out of work, respectively, in Denmark. Also, Trunks showed a much higher increase than any other category. While the others showed an average increase of 5-12% in the 6:00-8:00 range and of 4-10% in the 15:00-17:00 range, trunks showed an increase of 24% and 25%, respectively. This suggests that the performance of those roundabouts have a higher sensibility to congestion. We move to the days of the week. Figure 10 shows the average energy consumption per day of the week per roundabout category.

The figure shows similar consumption from Monday to Friday, with an average decrease of 5-8% during the weeks for all categories, except residential and trunks. The former shows an increase of 3% on Sundays and the latter, a decrease of 10% on Saturdays and 20% on Sundays. Again, it shows that trunks have a higher sensibility to congestion. Finally, we look at the months of the year. Figure 11 shows the average energy consumption per month of the year per roundabout category.

The figure shows a well-known pattern for EVs. The lower energy consumption in the months of July, August, and September (Summer in the northern hemisphere) is due to the higher temperatures, which improves battery efficiency [1]. Also, this figure casually validates the operation of the OBD device and how we calculate the energy consumption of the passes.

The seasonality analysis reveals two interesting findings. First, it shows, based on the hours of the day and the days of the week, that the performance of trunks have a higher sensibility to congestion than the other categories. And second, in the three figures we can
see two groups of roundabout regarding the energy consumption inside them: residential, unclassified, and tertiary roundabouts, with a higher average consumption, and secondary, primary, and trunk roundabouts, with an average of 10-16% lower consumption than the others.

5.3 Speed

Speed is an impactful aspect when it comes to the energy consumption of vehicles. As roundabouts are designed to increase traffic flow by avoiding idling, we look at how different roundabouts interact with the speed of the vehicles and how that relates to the energy consumption. Although roundabouts are designed to allow vehicles to pass through without having to completely stop most of the time, vehicles still have to reduce their speed before entering the roundabouts. In fact, many roundabouts adopt artifices known as traffic calming - to force this reduction in speed. For example, in Denmark, many roundabouts have particularly high central islands in order to discomfort the drivers and force them to better observe the traffic inside it. The measure reduced the accidents in roundabouts in Denmark by 24-84% [10].

Before we start the analysis, we believe it is important to show how the energy consumption changes in relation to the average speed of the vehicles we use in this study. For every trajectory in our dataset, for all its road segments, we calculate the energy consumption and the average speed of the vehicle. Figure 12 shows the average energy consumption for different intervals of speed, from 10 to 100 km/h. As we constantly use the road category of the roundabouts in this study, we group the road segments based on their road category as well.

![Figure 12: Average energy consumption per average speed per road category.](image)

Although the figure only shows the curves for the vehicles used in this study, EVs are known to have such a parabolic curve, regardless of the their make and model [2]. The purpose of this figure is twofold: to show that low and high speeds have the highest energy consumption, while the speeds between 50 and 70 km/h have the lowest, and that the road category has little to no effect on the consumption. Just like Figure 11, this figure casually validates the operation of the OBD device and how we calculate the energy consumption.

We start our analysis by looking at the difference in speed right before and after the roundabouts. The speed right before is the instantaneous speed of the last GPS+ point on the road segment entering the roundabout and the speed right after is the instantaneous speed of the first GPS+ point on the road segment exiting the roundabout. Consider Figure 2 for an example. Counting from left to right, the speed right before comes from the 5th point and the speed right after, from the 14th point. Figure 13 shows the average energy consumption inside the roundabouts per the speed difference right before and right after the roundabouts per roundabout category. We disregard the data for differences lesser than 0 km/h or greater than 25 km/h as there are few passes with said differences.

![Figure 13: Average energy consumption per speed difference before and after the roundabout per roundabout category.](image)

The figure shows that, the higher the difference in speed between before and after the roundabouts, the higher the energy consumption inside them. This doesn’t come as a surprise per se, as it is well-known that accelerating increases the energy consumption [5]. What’s really interesting about this graph is the linear behaviour across all categories. For trunks, for example, every 5 km/h difference results in an increase of around 51 Wh/km. For tertiary, every 5 km/h difference results in an increase of around 69 Wh/km.

We now look at how much the drivers tend to accelerate inside the roundabouts. Figure 14 shows the count, in percentage, for each speed difference per roundabout category. Again, we disregard the data for differences lesser than 0 km/h or greater than 25 km/h.

![Figure 14: Count of speed difference per roundabout category.](image)

The figure shows that the majority (78.6% for residential roads and 63.8% for trunks) of the vehicles pass through the roundabouts with an increase in speed between 0 and 10 km/h, regardless of...
the roundabout category. This result shows that most roundabouts prevent the vehicles from accelerating too much inside them, meaning that the speed of vehicles inside a roundabout isn’t going to be much different than the speed they were at when they entered it. This way, we now look at the distribution of the instantaneous speeds right before the roundabouts. Figure 15 shows the count, in percentage, for each instantaneous speed right before the roundabout per roundabout category. We disregard the data for speeds greater than 50 km/h as there are few passes with said speeds.

The figure shows that, as we go from residential to trunk roundabouts, the instantaneous speed right before the roundabouts increases. For residential roundabouts, most vehicles have a speed between 15 and 25 km/h, for unclassified and tertiary roundabouts, between 20 and 30 km/h, for secondary and primary roundabouts, between 25 and 35 km/h, and for trunks, between 30 and 40 km/h. This difference can easily be explained by the speed limit of the roads connected to the roundabouts. In Denmark, urban roads usually have a speed limit of 50 km/h, non-urban roads usually have a speed limit of 80 km/h, and motorways, 130 km/h [20]. Although we use a different classification system, our residential, unclassified, and some of the tertiary roads can be seen as urban roads, while some of the tertiary, secondary, and primary roads can be seen as non-urban, and the trunks can be seen as motorways.

Together, Figures 12, 13, 14, and 15 explain the performance among different roundabout categories. Figure 14 established that the roundabouts prevent the vehicles from accelerating too much inside them, albeit possible, while Figure 13 revealed the cost for this acceleration. Figure 15 showed that the average speed of the vehicles right before they enter the roundabouts based on their category. At residential roundabouts, the vehicles enter with an average speed of 20 km/h, while at trunks, they enter with an average speed of 35 km/h. By referencing Figure 12, we can say that, as we go from residential to trunk roundabouts, the increase in performance is tied to the overall increase in speed before and at the roundabouts, allowing the vehicles to travel closer to their optimum speed in terms of energy consumption.

To wrap up, we verify our claim. We look at the last instantaneous speed right before the roundabouts and the average energy consumption inside them, grouped by their category. Figure 16 shows the average energy consumption inside the roundabouts per instantaneous speed right before them per roundabout category. We disregard the data for speeds lesser than 10 km/h or greater than 45 km/h as there are few passes with said speeds.

Figure 16: Average energy consumption per speed before the roundabout per roundabout category.

Figure 16 corroborates our claim. It shows that the energy consumption inside the roundabouts have an intimate relation with the speed the vehicles are at as they enter the roundabouts. So much so that, by doing a polynomial regression of order two for each category (RES, UNC, TER, SEC, PRI, and TRU), we have the following coefficients of determination: 0.752, 0.802, 0.987, 0.996, 0.992, and 0.984, respectively. Showing, once again, how the energy consumption of the vehicles inside the roundabouts highly correlates to the speed they are at as they enter the intersections.

6 CONCLUSION

This paper used a large dataset of high-frequency spatiotemporal data to study intersections. More precisely, we used 98,228 trajectories, that together passed through 1,186 different roundabouts, for a total of 1,897 passes, to analyze and quantify how roundabouts impact the energy consumption of EVs. These are unprecedented numbers in the study of intersections and roundabouts.

The first goal of this study was to determine whether 1-Hz GPS sampling is fast enough to study intersections. While road segments can be studied with low-frequency sampling, intersections are much shorter and, therefore, require faster sampling. We used two metrics to evaluate that: the number of passes that didn’t register any GPS point on the roundabout segments and the number of points registered on those segments. For the former, out of the 198,534 GPS point on the roundabout segments and the number of points registered on those segments. For the latter, 97% of the passes registered at least two GPS points on the roundabouts (and the vast majority of those were due to the GPS device losing satellite coverage at the time). For the latter, 97% of the passes registered at least two GPS points on the roundabouts, while 51% of the passes registered at least six points. This shows that 1-Hz data is capable of capturing the intersection while providing enough information about it.

The second goal of this study was to analyze and fairly compare roundabouts regarding the impact they have on the energy consumption of EVs. We used three criteria for grouping: the radius of the roundabouts, their number of arms, and their road category. We showed that, overall, the energy consumption decreases as the
radius or the number of arms increases or as we move from residential to trunk roundabouts. The results showed that these three features have an intimate connection. Also, regarding the number of arms, we showed that exiting the roundabouts at the first possible arm after entering it has an energy consumption 27-37% higher compared to the other possible exits.

The seasonality analysis revealed that trunk roundabouts have a higher sensitivity to congestion compared to the other categories. While the other roundabouts showed a decrease in performance during the so-called rush hours - 6:00-8:00 and 15:00-17:00 - of 4-12%, trunks suffered a decrease of 24-25% during the same periods. Also, the analysis showed an overall separation between two groups of roundabouts regarding the energy consumption inside them: residential, unclassified, and tertiary roundabouts, with a higher average consumption, and secondary, primary, and trunk roundabouts, with an average of 10-16% lower consumption than the others.

Finally, we showed that the energy consumption inside the roundabouts are highly related to the speed the vehicles are at when they enter the roundabouts. Even though roundabouts are designed to increase traffic flow by reducing idling, safety aspects tend to force the vehicles to reduce their speed as they approach the intersection. We showed that, while inside the roundabouts, most vehicles tend to maintain their initial speed or increase it very little. So, for the roundabouts with worst efficiency, most of the vehicles enter them at a lower speed, while for the roundabouts with better efficiency, most of the vehicles enter them at a higher speed. For example, for residential roundabouts, most vehicles approach them with an average speed of 20 km/h, farther from the optimum speed range of the vehicle (50-60 km/h), while for trunk roundabouts, the average speed is 35 km/h, closer to the optimum range of the vehicle. Also, we quantified the cost the increase in speed inside the roundabouts has on the energy consumption of the vehicles as they pass through them.

Even though this study achieved its goals and revealed many interesting aspects regarding the efficiency of the roundabouts, there are other aspects to explore. For future work, we would like to investigate whether the lane used to enter the roundabout or different types of signalization have any impact on the energy consumption of EVs.

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