# Towards Dynamic Isochrone Mapping Accounting for Uncertainty

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Short Paper
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**Abstract**

Isochrone Mapping has been used since the late 19th century as a planning and visualization tool in various domains, such as transport planning and hydrology. In the past, isochrone calculation was based mainly on static properties and therefore also yielded static maps. This resulted in a potentially significant — and at the same time unquantifiable — degree of uncertainty. Today however, advances both in information technology and in the availability of input data allow much more nuanced views on the subject.

This paper gives an overview of work on dynamic factors that contribute to uncertainty in isochrone calculation and mapping. Various application scenarios and their constraints are discussed, and open research challenges and possibilities identified. Finally, we present preliminary results from a practical approach to quantifying uncertainties in isochrone calculation for motorized individual transport based on Monte Carlo simulations and data from open routing APIs.

**Keywords:**

accessibility analysis, isochrone map, travel time, uncertainty, transport science

## 1 Introduction

An isochrone (Greek: iso = equal, chronos = time) is a line or area on a map that denotes events with equal duration, or events taking place at the same time as each other. Isochrones are often used to visualize the accessibility of certain spatial entities, such as travel times from a certain point of origin. The first cartographer to draw such a map was Francis Galton 1881 (Bielecka and Bober 2013; Dovey, Woodcock and Pike 2017). His Isochronic Passage Chart for Travellers displayed how many days it took to travel to any place in the world from London without incurring unreasonable cost. However the quality of the data and its spatial coverage were naturally rather low, so the map could only be considered a rough estimate.

While data quality has increased greatly since then, uncertainty is often inadequately considered in isochrone calculation and mapping. The goal of this work is to address this issue and develop a method to measure and present the uncertainty of isochrone maps. Such an uncertainty metric may contribute to better decision making in urban and transport planning.

## 2 Isochrone Mapping

Following Galton's work, geographers, and transport and urban planners started to use isochrone maps as a tool to analyze and visualize the relationship between movement and time (Dovey, Woodcock and Pike 2017; Bielecka and Bober 2013). In particular, the map's strength lies in visualizing the accessibility of localities (Doling 1979; Berg et al. 2018). In recent years, through better computing power and faster routing algorithms (Baum et al. 2015), isochrone map generation has become much easier. Still, due to the high complexity and uncertainties involved, it is common to reduce the number of elements for consideration to just a handful for any one use-case. According to Dovey, Woodcock and Pike 2017, there are three primary uses for isochrone maps:

1. Comparing the accessibility of any given location at a given time for different modes of transport. For example: Allen 2018 linked travel times to network edges and compared the reachable edges by travel mode (e.g. bicycle and public transport). O'Sullivan, Morrison & Shearer 2000 used timetable and street network data to generate isochrones for travel by public transport.
2. Comparing the accessibility of locations for different time constraints – visualizing inequities of access. Such maps are developed yearly by the German Federal Institute for Research on Building, Urban Affairs and Spatial Development to show spatial transport-related accessibility in Germany (Schwarze et al. 2019).
3. Visualizing the effect of potential changes to help urban and transport planners. For instance, Berg et al. 2018; Efentakis et al. 2013 used isochrones with dynamic traffic and demographic data to look at what proportion of a population was unable to access a certain location within a given travel time.

As decisions and constraints vary according to individual demands, there is no single type of accessibility and isochrone map (Schwarze et al. 2019; Strubelt & Wegener 2001; Handy & Niemeier 1997). Instead, we must consider various factors and the spectrum of possible applications for isochrone maps. These factors were categorized into four accessibility components by Geurs & Van Wee (2004):

1. The land-use component considers "amount, quality and spatial distribution" of opportunities (e.g. jobs, shops, health, social facilities) and their demand.
2. The transportation component characterizes the individual (monetary or temporal) effort to cover the distance between the point of departure and the destination by one or more means of transport.
3. The temporal component describes the temporal availability of opportunities (e.g. opening times of shops) or individuals to engage in certain activities and their dynamic variability (weather, traffic load).
4. The individual component reflects the needs, abilities and opportunities of individuals. These factors depend on various attributes of the individual (e.g. age, income, physical condition or educational level).

These accessibility components can also be regarded as sources of uncertainty and thus reflect the factors that need to be considered when creating isochrone maps. Our goal is to explore how this can be approached effectively and efficiently.

## 3 Dynamic Isochrone Mapping and Uncertainty

In order to generate isochrone accessibility maps accurately, ideally all factors according to Geurs & Van Wee 2004 need to be taken into account (see Fig. 1).

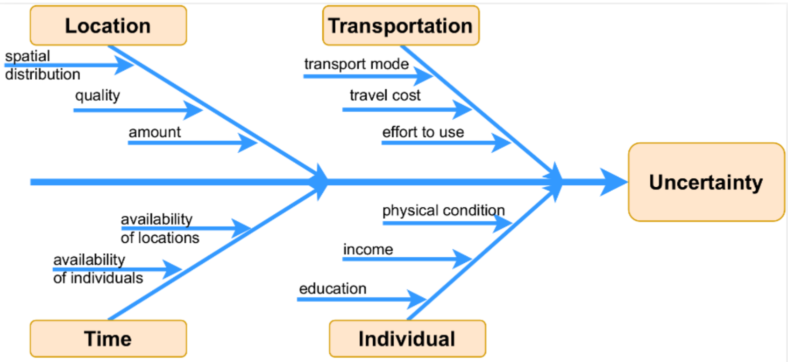


**Figure 1:** Accessibility components as sources of uncertainty in isochrone mapping.

In addition to understanding where uncertainty may stem from in isochrone mapping, there is another important aspect to consider: the degree of uncertainty that is acceptable from a user's point of view, which strongly depends on the application scenario, as do the constraints for each of the four components above. For instance, when planning a vacation, a higher degree of uncertainty concerning the travel time is likely to be acceptable, and the choice of mode of transportation may to some extent be flexible, whereas financial constraints will probably be more rigid.

However, there are other application scenarios that are completely different. If we were to apply isochrone mapping to determine which areas of a city can be reached by emergency response services (police, firefighters, ambulance), the time taken to arrive at the scene is (in some countries) constrained by law and too large an uncertainty is unacceptable. On the other hand, there are practically no individual components in this scenario.

In law enforcement, projecting which way a fugitive may have fled and what locations they could have reached can provide crucial information for apprehending criminals quickly. In such scenarios, the predominant source of uncertainty are individual factors.

Although there are a lot of studies which have used and developed isochrone maps to visualize specific forms of accessibility (Marciuska & Gamper 2010; Dovey, Woodcock & Pike 2017), few of them have included dynamic factors in their isochrone calculations (Efentakis et al.

2013; Berg et al. 2018). While there exists a lot of research about uncertainties in point-to-point vehicle routing, the level of uncertainty in isochrone mapping remains quite unclear.

Open routing APIs like Valhalla or GraphHopper (which are growing in importance) allow us to incorporate information on the dynamics of traffic into isochrone mapping and leverage this for decision making processes, which is a clear need, especially for emergency response services (Hu et al. 2020; Green et al. 2014).

## 4 Practical Isochrone Mapping Based on Open APIs

In this preliminary work, we take into account the three components location (coordinates of isochrone origins), time (start and range) and transport (mode) in a Monte Carlo simulation with the goal of reaching an uncertainty measure for isochrones. Due to its high complexity and the lack of available data, we disregard the individual component.

### Data and Methodology

The general approach is to construct both static isochrones (i.e. ones that do not take dynamic factors into account) and dynamic isochrones, which incorporate the relevant traffic information for time and place in the accessibility mapping (see Figure 2). The degree of uncertainty can then be expressed by comparing the areas of reachability as determined by the two different types of isochrone.

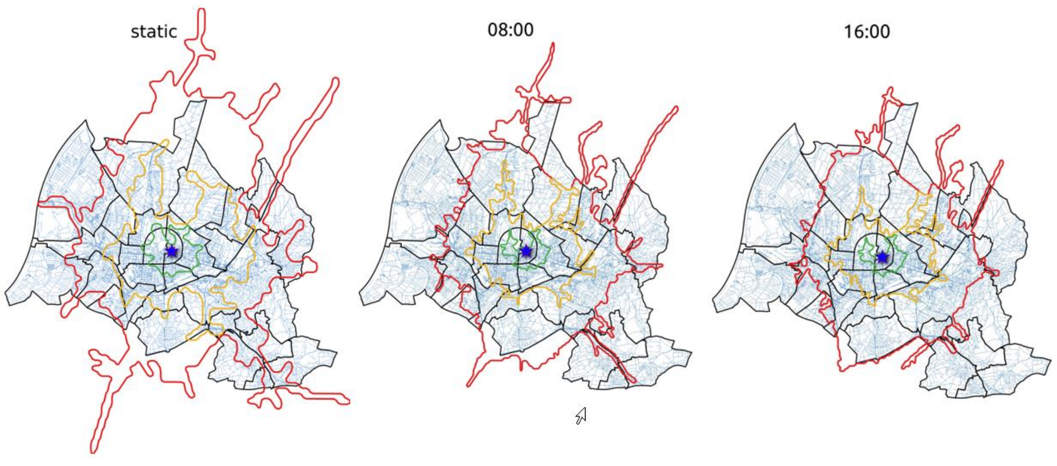


**Figure 2:** Map visualization of calculated isochrones. The static isochrone (left) does not take the traffic situation into account, whereas the dynamic ones do. The reduced reachability ranges, which differ depending on the time of day, show up cleary.

For this, we find that data from the HERE Routing API is fit for our purpose. The calculations of the isochrones are based on the passenger car as transport mode and road network data, for instance speed and turn restrictions.

HERE Routing is a cloud service for in-car navigation systems found in over 150 million vehicles, or 80% of road vehicle navigation systems in North America and Europe (Morlock et al. 2019; HERE Technologies n.d.). We can therefore assume that HERE Technologies provides data that is of sufficient quality for our purposes. Routing services exist for various modes of transport (car, pedestrian, public transport, truck and bicycle) as well as any combinations of these. Results are either a simple (temporal or distance) shortest path between two points or a matrix for a set of shortest paths between multiple points, such as the isochrone mapping. Furthermore, live or historical traffic data can be taken into account, so we can compare temporally different routing results. Access to HERE Technologies' data is possible via a simple REST API.

First, we generated evenly distributed isochrone start points within the City of Karlsruhe, Germany, which were map matched to car accessible roads; for each of these points, we calculated isochrones with a range of 15 minutes. Afterwards, we divided the results into two different categories: (1) static isochrones, which do not consider any dynamic factors; (2) dynamic isochrones, which utilize HERE Technologies' dynamic traffic model for calculation. For the latter category, we chose January 13th, 2020 – a Monday – as the investigation date, so that the traffic situation was not distorted due to the COVID-19 pandemic. Furthermore we investigated the changes of the isochrones over the day, by calculating them at each full hour.

In the next step, we calculated the area ratio between the dynamic isochrones and the static isochrones, and used histograms to visualize the distribution of the area difference ratio over the day. Finally we investigated the course of the mean and variance values of the area differences.

## Preliminary Results and Discussion

The 24 histograms – one for each full hour of our investigation date – revealed the distribution of the area difference ratio of these isochrones. For the illustrative purposes, we have selected six representative histograms, as shown in Figure 3, for January 13th, 2020, with the timestamps: 5:00, 7:00, 11:00, 16:00, 18:00 and 22:00. The x-axis represents the ratio of the isochrone area differences and the y-axis represents the relative frequency. Each histogram shows the ratio distribution of a certain timeframe. The results show that nearly all dynamic and static isochrones have similar area size (the ratio approaches 1) during the night, between 22:00 and 05:00. This means that during the night there is nearly no dynamic isochrone uncertainty. This is to be expected, since during the night there is very little traffic on the roads. Between 5:00 and 7:00, a trend of increasing dispersion and a shift of the mean ratio value is identifiable – showing the first traffic peak in the morning. As the day progresses, the distribution skews towards the left due to the decreasing of the ratio value, which reaches its minimum at about 16:00. We may assume that this is caused by the evening traffic peak, following which the distribution starts to skew back towards the right until 22:00, when there is again nearly no difference between the dynamic and static isochrones.

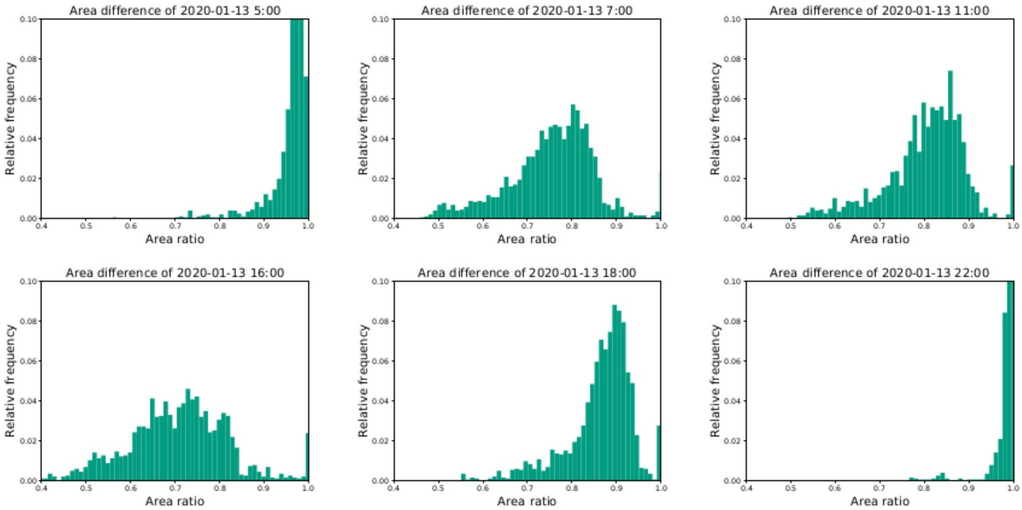


**Figure 3:** Selected histograms of the case study: The x-axis represents the area difference ratio between dynamic and static isochrones, and the y-axis represents the relative frequency. The area ratio varies over the time. In extreme cases in the daytime, there is an area overlap of only 40%.

Figure 4 shows the variance and the mean values of isochrone differences over the day. It should be noted that the y-axis of the means graph is reversed to allow a better visual comparison with the variance graph. When we look at Figure 4, we can see two big changes in the course of the curves. The first jump can be seen between 5:00 and 7:00. Between those two timestamps, the mean value has dropped significantly; simultaneously, the variance of the distribution has increased very significantly. This indicates that (1) the dynamic and static isochrones are quickly becoming different in size; (2) the variability of this difference is growing rapidly. Between 77:00 and 13:00, the curve remains relatively constant for both values, showing only small changes, or even small decreases of the traffic volume, at noon. From about 13:00, the traffic volume starts to increase until it reaches its peak at 16:00, when the mean area difference between both types of isochrone is the greatest. Finally, in the last major change of both values, the variance declines rapidly between 16:00 and 21:00, while the mean ratio increases towards 1, showing the declining traffic volume during the evening. There is another interesting result to be seen in Figure 4: a similarity between the daily courses of mean and variance. We interpret this as a positive correlation between the average uncertainty and the spatial uncertainty distribution.

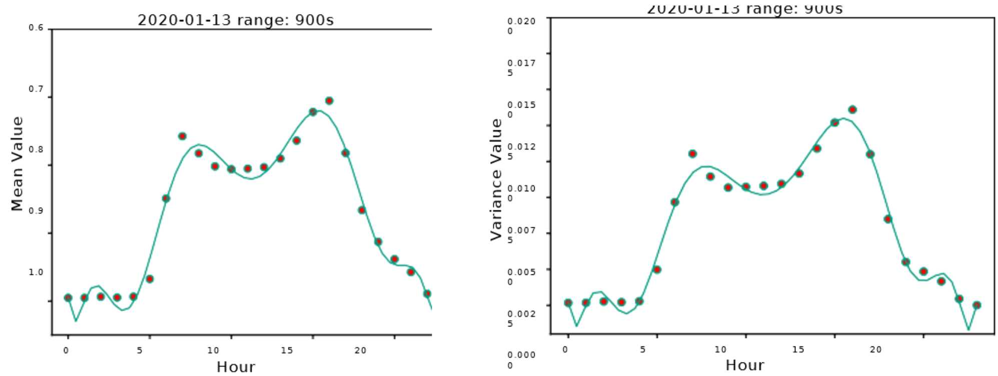


**Figure 4:** Uncertainty mean and variance over the day. The y-axis of the mean figure is reversed to allow a better visual comparison. A clear similarity between the courses of the mean and of the variance can be seen.

To summarize, we can say that there is a significant difference between the dynamic and the static isochrones during the daytime, between about 6:00 and 21:00. At the same time, there is also a high variance of the distribution. During the night, we have a low variance value and almost no difference between the static and dynamic isochrones, a result which we can interpret as follows: during the day there is significantly more traffic, and its distribution is more dispersed than during the night. In addition, there is a possible link between the traffic distribution (variance) and the total amount of traffic (mean difference ratio). The extent of the dynamic uncertainty should therefore be taken into account when a static isochrone map is used to support decision making.

## 5 Conclusion and Future Work

This work provides an overview of the scope of isochrone mapping and its application scenarios, factors that contribute to uncertainty, and the state of the art and current limitations — especially in handling dynamic factors.

Based on this theoretical background, we developed a practical approach that uses a Monte Carlo simulation to estimate the distribution of uncertainties in formerly static isochrone maps. Our preliminary results show the variability of the distribution over a single day and clearly highlight the need for more nuanced approaches in isochrone generation.

In future work, we plan to expand our Monte Carlo simulation by taking other uncertainty parameters into account. Firstly, we intend to investigate the impact of spatial variability on isochrone mapping. Secondly, we will address other open research challenges, such as adequate visualization of dynamic information uncertainties (MacEachren et al. 2005).

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