ENGINEER 2PX3: Integrated Engineering Design Project 2

Self-Driving Infrastructure Final Project Report

Team: SDI – 06

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Erin Boshell EBoshell

Executive Summary

This report provides a detailed documentation of our final design for a high-performance, robust, efficient, safe, and environmentally friendly intersection, that can accommodate both self-driven and human-driven vehicles. The report has information regarding our design decisions as well as an analysis of our design aided by the PERSEID framework. The report also establishes the scope of the project as well as the objectives and constraints that we have defined for our design. The outcomes realized thus far are a simulation suite of empirical experiments, a finalized intersection design that satisfies all project objectives and constraints, a decision matrix, a design evaluation in which all changes made to the initial recommendations are explained, a summary of the feasibility report as well as a discussion on the effect that client requests had on the design. Additionally, supporting materials such as the code, as well as its outputs are presented in the appendices. Our design is a four-way roundabout intersection, which we recommend being constructed in a rural area. We recommend that the intersection is used by traffic which is as close to being 50% human-driven and 50% self-driven vehicles. Additionally, the traffic should also have approximately 25% of the vehicles be turning vehicles, of which 50% are left-turning and 50% are right-turning. The advantages of this solution compared to other design options discussed was a better achievement of both major objectives: performance and safety. The next steps that we recommend to the client are to publicize the infrastructure design and construction plan to the public and then begin hiring workers for constructing the intersection.

Introduction

With the influx of new technology involving self-driven vehicles and vehicle to vehicle communication, the possibility for fully autonomous personal transport systems in the near future is growing. However, in the transition period which exists at present, there is a need to redesign road infrastructure to better integrate self-driven vehicles into the pre-existing population of human-driven vehicles. One major aspect of road infrastructure that is need for design reconsiderations is the arterial road intersection. As engineers working for a consultancy firm, our job was to come up with a design for an intersection with the main objectives being effective and safe. We were to then analyze this intersection using the four layers of the PERSEID framework to evaluate whether it was feasible or not. Through this analysis we were able to narrow down the traffic parameters for which the design was feasible. Part of the feasibility analysis and our general design decisions were informed both directly and indirectly by the various stakeholders that we had to consider. The main stakeholders that we considered was the client with whom we had weekly meetings (informing our progress and addressing their requests), the drivers of the human-driven vehicles, the owners of the self-driven vehicles, the manufacturers of the self-driven vehicles, pedestrians, and residents in the area surrounding the proposed intersection construction location. The scope of the project included the generation of the project design, writing the simulation suite to perform tests on the simulation design, and interpreting the results of these tests through the help of the PERSEID framework.

Decision Process

Our initial recommendation was to have a standard four-way intersection in a densely populated urban area. We wanted the original design to support a high volume of traffic, where the majority of this traffic would be self-driven cars. Our system would be designed to integrate self-driven cars within this standard intersection easily. We evaluated our initial recommendation by conducting a feasibility analysis using the PERSEID method. While conducting our analysis, we found that our design raised many concerns. All of the changes that we made to get from our initial to final recommendation were done in an attempt to create a feasible design that could be integrated into the real world successfully. We first looked at technical performance; this is where we decided that our primary objectives would be centred around safety, fairness and efficiency. We wanted to reduce traffic, have an accident rate of as close to zero as possible and have equal priority between the different users. As we moved forward in our analysis, we found many scenarios where safety and fairness took precedence over efficiency. For example, if a pedestrian wanted to cross the intersection, it would increase the queue time for the cars waiting to pass. The time taken to wait for the pedestrian would affect the flow of traffic and, in turn, the efficiency of our system. However, if we did not let pedestrians use our intersection or if we gave them minimal time to cross, this would be unfair. This is where we realized that efficiency would have to be compromised to ensure our design is safe and fair. We then worked through socio-cultural concerns. Our original proposal of designing the intersection with self-driven cars as the primary user and having every other user deemed a lower priority was unfair. Some users may be unable to afford or prefer not to use a self-driven car, so it would be socially wrong to deem them as "secondary" within our system. This was when we decided to make the first change to our original recommendation. Instead of having self-driven cars as the main focus of our design, we would have equal priority among all users. Pedestrians, self-driven and human-driven cars would all be at ⅓ priority in our system, meaning no one user would take precedence over another.

The last layer of our feasibility analysis was conducted by looking into the environmental concerns our design could impose. We realized that our design raised many environmental concerns as implementing a large intersection in a densely populated area would have disproportionately large, adverse effects on the environment around it. Our original design would have impacts from greenhouse gasses from the cars that utilize fossil fuels, land usage, noise pollution, and the resources needed to build our intersection that are energy intensive. After analyzing these possible impacts, we made the most changes to our design to compensate for these adverse effects. We decided to change the location of our intersection from a densely populated, urban area to a more rural, less populated area. This would mean our intersection would be smaller as we would have to account for a lower volume of traffic. This change of location would also reduce land usage, noise pollution, and the energy-intensive resources needed for our original design. With this new location and a smaller volume of traffic, we would improve all of our performance-related objectives. We predict there will be shorter queue times which will improve traffic flow and our system's efficiency. There would also be a lower accident rate as there is a lower probability of an accident occurring in this revised system, which would aid our safety objective for reducing accidents. We also decided that the exact location of our intersection would not be chosen by the frequency of self-driven or human-driven cars in that specific location. We will implement the intersection in a space where self-driven and human-driven cars will have equal access.

We realized when designing our system that we could not make a realistic design that was one hundred percent feasible. This is why we decided to minimize most of the many environmental concerns in a way that our performance-related objectives could improve. As a team, we realized there was still a probability of accidents within our intersection. We would have a designated lane for left and right turning to reduce accidents, but with human-driven cars, there is always a layer of uncertainty with their response mechanisms. This is why we made our final design decision to have our intersection become a roundabout. This system would follow the same parameters as our rural intersection, but the roundabout format would increase safety, fairness and efficiency. The roundabout would also help reduce environment concerns even further. The system will minimize traffic and delays, which will mean less air pollution and fuel consumption that vehicles idling in the intersection could cause [1]. We believe our final recommendation of a roundabout in a less densely populated area could be integrated easily and effectively into the real world. All of the changes we made to our initial recommendations were done to reduce the impacts our original design could have imposed on its users and the world around it.

Decision Matrix							
Options	**Criteria**						
	Performance Related Objectives			**Remaining PERSEID Layers**			
	Safety	**Fairness**	**Efficiency**	**Socio-cultural Appropriateness**	**Ability to Minimize Regulatory Concerns**	**Ability to Minimize Environmental Concerns**	**Total /30**
Initial Recommendation (intersection in urban area)	4	2	2	2	5	1	16
Revised Recommendation (intersection in a rural area)	3	5	4	5	5	4	26
Final Recommendation (roundabout in rural area)	5	5	5	5	5	5	30

Table 1 Decision Matrix. Each criteria ranked on a scale of 1-5. Where 5 is high and 1 is low. This clearly shows that our Final Recommendation has the highest score /30, so it is the best choice.

The first client request was focused on the travel time through our intersection. The request was a graphical representation of the average travel time as a function of the load, which can be seen in Figure 1. Our graph showed that as the number of vehicles increased, the travel time would also increase. A high travel time signifies that users will have a longer queue time, and there is likely more congestion within the intersection. This means that with a higher load, there will be more traffic, which would reduce the efficiency of our design. Our original proposal of having our intersection in a densely populated area would raise concerns based on this request. A densely populated area would bring in a large load of vehicles, meaning our intersection would likely have traffic and would not be as efficient as we originally thought. Our original solution was to impose a restriction on the number of vehicles that could use our intersection at a single time to lower the load and, respectively, the travel time. However, this raised concerns within our feasibility analysis. We then decided to implement our design in a less densely populated area to help reduce this issue. The new location would mean a lower load and, in turn, a lower average travel time through our intersection. This change would improve the efficiency of our system. When revisiting this client request after making our final recommendation of a roundabout, we found that even if there were a large load, the system could compensate, as there is a constant traffic flow, which reduces queue times and efficiency. This client request allowed us to acknowledge how the load could put stress on our system that we needed to reduce.

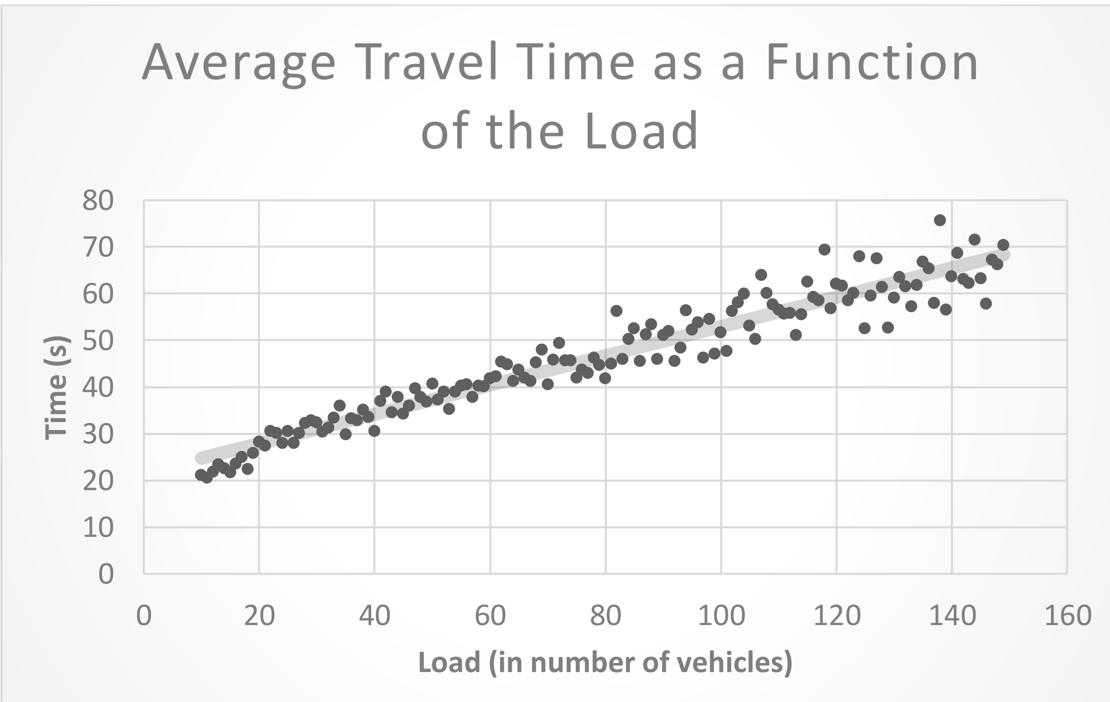

Figure 1 Average Travel Time as a Function of the Load

The second client request compared the difference in the performance of self-driven and human-driven cars. We compared the types of cars based on three criteria, the accident rate per year, response rate and time they take to cross an intersection, as seen in Figure 2. We found that human-driven cars have a much higher annual accident rate because of their unpredictability. Human-driven vehicles have a slightly higher response time because self-driven cars have programmed response mechanisms, whereas human-driven cars do not have this advantage. Human-driven cars take longer to cross an intersection, as there is a slight delay because of the human's response time, whereas the self-driven car does not have that delay. We concluded that self-driven cars would make the intersection much more efficient and safe. Having only self-driven cars in our intersection would reduce accidents and traffic. However, while conducting our feasibility analysis, we determined that prioritizing self-driven cars in our system was not socially appropriate. This was another scenario where we chose to sacrifice some efficiency for fairness because we chose to have equal priority between both types of cars.

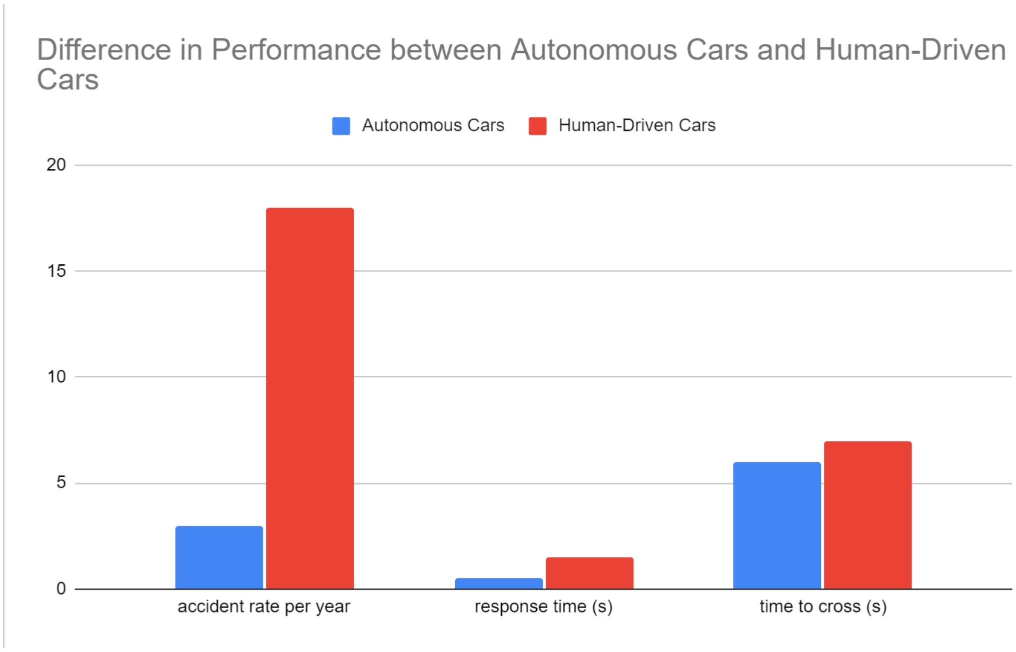

Figure 2 Difference in Performance Between Autonomous Cars and Human-driven Cars

The third client request was to add a way to account for accidents and a way to measure the severity of these accidents within our simulation. The main objective of our design was to improve safety by reducing accidents. We made a graphical representation of the severity of the crash vs the changing variable of stop and clear time, as seen in Figure 3. We found that there would be more severe collisions with lower stop and clear times. The longer queue times in our simulation would reduce the severity of accidents. We believe this is because, with longer times, the intersection has more time to adapt to the changing position and frequency of the vehicle. Whereas, if the times are short, there is much more frequent movement within the system. We previously determined that human-driven cars have a longer response time and clear time. So, it would make sense that more accidents would occur if they had a lower clear time. For self-driven cars, there is a higher chance of malfunction or accident if they have clear times faster than what they are capable of. The concern of accidents would be reduced when we moved the location of our design to a less densely populated area, as the clear time would become less dependent on the number of cars in the intersection at a given time. Having our system as a roundabout would reduce this concern even further. A roundabout reduces accidents and improves queue times because of the way it functions.

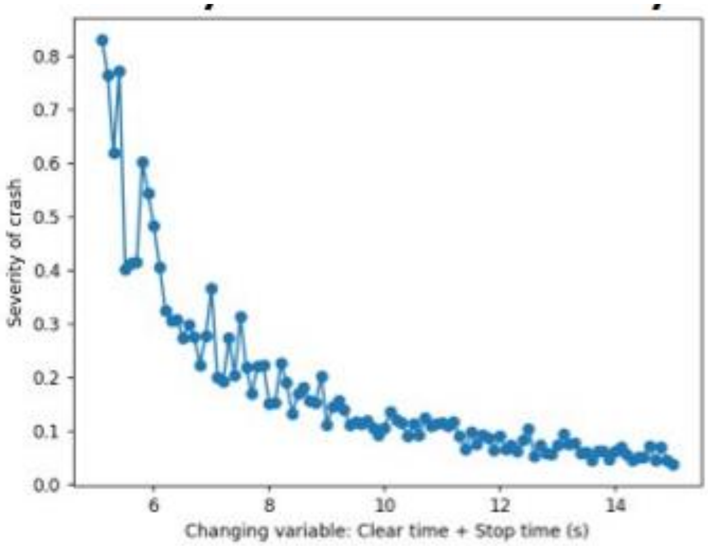

Figure 3 Severity of Crash vs Changing Variables of Clear and Stop Time

The final client request was to add a way to measure the estimated emissions to our simulation. We found that our initial recommendation would have the highest value for estimated emissions, as there was a higher load, increased traffic congestion and in turn, many cars would be idling and producing emissions. We reduced this concern by changing our location. The less densely populated area meant less traffic, and cars would have less idling. However, since there is still a queue for the intersection, the cars would still produce emissions as they wait to cross. This client request helped us determine our final design recommendation, as we wanted to reduce this environmental concern. The small amount of fuel wasted by one car idling at an intersection is exponentially increased when considering the number of cars passing through the intersection daily, resulting in a massive quantity of fuel wasted [2]. This waste of fuel and the production of emissions is a huge environmental concern, and it was still prevalent in our revised design. Our final recommendation of a roundabout drastically decreases vehicular emissions and fuel consumption by reducing queue times as there is a constant flow of traffic.

Final Proposed Design

Our final design is a four-way roundabout intersection, as illustrated in figure 6. It will be located in a rural location, and recommended to be in a location with traffic that consists of approximately 50% human-driven and 50% self-driven vehicles. Furthermore, it is also recommended for the traffic at the chosen location to consist of 25% turning vehicles, of which 50% would be turning right and 50% would be turning left. Tables 2 and 3 show that the parameter value ranges that this combination falls in provides favourable environmental and safety characteristics.

NUMBER OF CRASHES FOR A CONSTANT LOAD OF 50 VEHICLES										
		Right turn probability								
		10%	20%	30%	40%	50%	60%	70%	80%	90%
Self Driving Percentage	10%	0	0	0	1	2	0	0	1	0
	20%	0	0	0	0	0	1	0	0	0
	30%	0	0	1	0	0	2	0	0	0
	40%	0	0	0	0	0	1	0	0	0
	50%	0	0	0	0	0	0	0	0	0
	60%	0	0	0	0	0	0	1	1	0
	70%	0	0	0	0	1	0	0	0	0
	80%	0	0	0	0	0	0	0	0	0
	90%	0	0	0	0	0	0	0	0	0

Table 2: Number of crashes for a constant load of 50 vehicles

IDLING TIME CARBON DIOXIDE EMISSIONS* (in Kilograms)										
		Right Turn Probability								
		10%	20%	30%	40%	50%	60%	70%	80%	90%
Self Driving Percentage	10%	422.4079	468.9039	493.0629	420.3292	481.4831	517.1194	476.2727	434.4048	470.2066
	20%	415.8468	430.6393	358.9537	411.6801	446.1419	357.1022	366.2705	393.1186	454.6199
	30%	371.1747	443.091	349.3272	381.5593	401.2774	435.5667	417.8102	368.1848	360.2078
	40%	474.375	448.2624	394.908	372.4043	378.7099	473.6533	415.5647	356.331	473.3293
	50%	425.9159	346.1864	372.9417	336.3287	367.5189	388.152	376.1856	438.6875	392.2767
	60%	384.0267	348.7385	384.3127	320.2357	366.6116	444.2074	444.1415	317.7672	425.2698
	70%	410.7674	313.8503	387.6928	403.0855	341.4401	340.9044	289.1182	364.7427	357.2659
	80%	384.5046	354.1265	380.6195	349.1391	377.4411	328.6164	431.791	350.9272	417.0503
	90%	361.7198	313.5689	310.052	364.8252	322.9743	324.6869	294.0631	201.6141	340.8356
							*For a constant load of 50 vehicles			

Table 3: Idling time carbon dioxide emissions in kg

We chose a roundabout design for our intersection after careful deliberation and debate. Roundabouts allow for a seamless experience as vehicles do not need to stop unless they are yielding to a vehicle currently inside the roundabout. Additionally, it alleviates environmental concerns due to the reduction of queue time. It reduces vehicle emissions and fuel consumption drastically, leading to less air pollution and resource use. With the added effect of being located in a rural intersection, it becomes unlikely for cars to have to yield to oncoming traffic in the roundabout, meaning most interactions with the roundabout will have no queue or stop time whatsoever. However, in the case of a particularly large load of traffic, we believe the roundabout system will be able to efficiently accommodate the vehicles and provide a lower queue time than a regular four-way stop sign.

Our final deliverables includes a model/diagram of our design, various simulation suites of empirical experiments, and a fully coded simulation showcasing our intersection in action. Our simulation code for a roundabout intersection is generally realistic, with minimal deviations from real-world roundabout behaviour. It can simulate most ordinary traffic patterns and interactions, but it may fall short in more complex or unusual cases. It represents basic roundabout dynamics reliably and may be used for general simulations and studies.

Our objective to have as few accidents as possible was met, as can be seen in table 2. The crashes approach zero as the percentage of self-driven cars increases, and the number of crashes elsewhere in the probability chart is similarly quite low, indicating that these accidents are occurring due to unavoidable human error. Similarly, we met our objective to have a minimal environmental impact. In table 3, we can observe that for a constant load of 50 vehicles, the idling time carbon dioxide emissions range from 320 to 372 kilograms. These meet our objective of having below 400 kilograms for the appropriate set of data (around 50% self-driving and 50% human driven). Furthermore, we intended to have an intersection which treated self-driving vehicles and human-driven vehicles equally, and intended for the performance to reflect that. We achieved this, as can be seen in figure 2, where although the accident rate varies greatly (as is expected), the response time and the time to cross are both very similar (with differences of up to 1 second, indicating we are pushing the boundaries of how quickly human-driven cars can cross. Lastly, we achieved our objective of designing an intersection where a larger load could be properly accommodated. As detailed in figure 1, as the load increases, travel time increases but at a slow and constant rate, indicating that traffic jams do not occur and cars continue to pass smoothly, albeit with a slightly higher travel time due to the volume of cars. We measured a travel time of 70 seconds for a load of 150 cars, which is quite low given the remarkable load.

Given the client's week ten request, there are several changes required. For the first scenario of 90% of cars traveling from north to south, to meet the increased traffic volume in the North-South route, additional lanes could be built to the roundabout entry and departure sites, providing for smoother traffic flow. Furthermore, extra lanes could be created near the roundabout entry and departure sites to accommodate the increased traffic load on the North-South route, resulting in smoother traffic flow. To guide drivers and identify the right lanes for their desired directions, clear signage and lane markings should be in place, minimizing confusion and potential conflicts.

For the second scenario of 95% of traffic from North, South, and East, and only 5% from West, given the low volume of traffic from the West, a dedicated lane or reduced lane capacity could be assigned to meet the lower traffic volume, while providing additional lanes to the higher volume directions (North, South, and East). Additionally, to prevent conflicts with the greater volume directions, a traffic island or splitter island could be erected to separate traffic from the West direction.

For the third scenario of 95% of traffic traveling from East to West or vice versa, because traffic is largely flowing from east to west or vice versa, all directions of traffic may be required to stop, potentially causing delays. To alleviate this, traffic signals might be put at the roundabout's entry and departure locations, providing for a controlled and regulated flow of traffic from all directions while maintaining safety and minimizing delays. The roundabout's size and geometry might also be changed to allow for more efficient traffic flow in the East-West or West-East directions, which would accommodate the increased traffic in those directions. Lastly, alternative routes or bypasses could be developed in order to reroute some traffic away from the roundabout, decreasing congestion and delays.

Conclusion

The executive summary's information makes it abundantly clear that the design team put a lot of thought and effort into developing a high-performance, sturdy, efficient, safe, and environmentally friendly intersection that can support both autonomous and human-driven vehicles. The team has offered thorough documentation of the final design, which covers design choices, analysis, and auxiliary materials like code and results. The group has suggested building a four-way roundabout intersection in a rural area that can handle traffic that is as close to being driven by humans and self-driven vehicles at 50% each, with about 25% of the vehicles turning, of which 50% turn left and 50% turn right. The team has outlined the benefits of this approach over alternative design possibilities and how it more effectively meets the two main goals of performance and safety.

The team's suggested next actions are to make the infrastructure design and construction plan publicly known and to start hiring employees to build the intersection. Overall, the design team addressed the project's objectives and restrictions successfully and offered a well-considered, workable solution that matched the client's needs.

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[3] X. Li, "The symmetric intersection design and traffic control optimization," Transportation Research Part C: Emerging Technologies, vol. 92, pp. 176–190, 2018.

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[6] I. Shatnawi, P. Yi, and I. Khliefat, "Automated intersection delay estimation using the input–output principle and turning movement data," International Journal of Transportation Science and Technology, vol. 7, no. 2, pp. 137–150, 2018.

Appendix

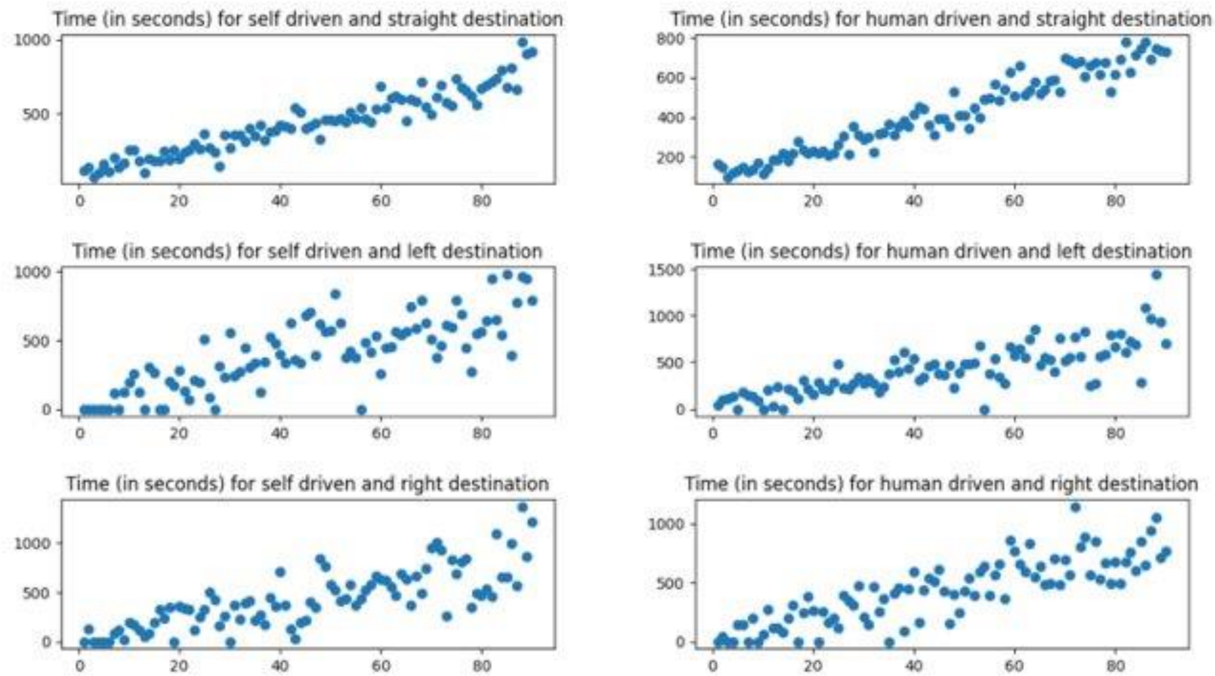

Figure 4: Time in seconds depending on various factors

```python
if event.direction == North:
  if self.North == []:
    self.ready_for_North = False
  self.North.append(Driver)
  New_event = Event(Stop, self.clock_time + Driver.get_stop_time(), North)
  self.events.add_an_event(New_event)

elif direction_of_event == East:
  if self.East == []:
    self.East_ready = False
  self.East.append(Driver)
  New_event = Event(Stop, self.clock_time + Driver.get_stop_time(), East)
  self.events.add_an_event(New_event)

elif direction_of_event == South:
  if self.South == []:
    self.South_ready = False
  self.South.append(Driver)
  New_event = Event(Stop, self.clock_time + Driver.get_stop_time(), South)
  self.events.add_an_event(New_event)
```

```python
elif:
  if self.West == []:
    self.West_ready = False
  self.West.append(Driver)
  New_event = Event(Stop, self.clock_time + Driver.get_stop_time(), West)
  self.events.add_an_event(New_event)
```

```python
#Self-Driving 06                    Gurleen Kaur Rahi, Erin Boshelle, Vinithkumar Thyagarjan, David

from ast import List
import random

#Initializing variables

Stop = "Stop"
Depart = "Depart"
Arrival = "Arrival"
Mean_Arrival_Time = 7
Vehicle_speed = 2
Roundabout_size = 6
North = Roundabout_size*3
South = Roundabout_size*9
East = Roundabout_size*1
West = Roundabout_size*2
Capacity = Roundabout_size*5
Events = False

```

```python
#For Driver

class Driver:

  def init(self, name, time_of_arrival, direction_of_arrival, direction_of_departure):
    self.name = name
    self.time_of_arrival = time_of_arrival
    self.direction_of_arrival = 0
    self.signal_turn = False
    self.position = direction_of_arrival
    self.direction_of_departure = direction_of_departure

#For Simulation

class Simulation:

  upper_time_of_arrival = Mean_Arrival_Time * 2

  def init(self, total_number_of_departures):
    self.num_of_departures = 0
    self.total_number_of_departures = total_number_of_departures
    self.clock = 0
    self.North = []
    self.South = []
    self.East = []
    self.West = []
    self.center = []
    self.Events = Events
    self.total_num_of_times = []

  def enable_Events(self):
    self.Events = True
```

```
def run(self):
  while self.num_of_departures <= self.total_number_of_departures:
    self.generate_arrival_time()
    self.operate_entrances()
    self.operate_roundabout()
    self.clock_time = self.clock_time + 1


  print(self.total_num_of_times)

def operate_roundabout(self):

  index_removal = []

  for i in range(len(self.center)):
    if self.center[i].position == self.center[i].direction_of_departure:
      index_removal.append(i)

    if self.center[i].position >= Capacity - Vehicle_speed:
      self.center[i].position += Vehicle_speed - Capacity

    else:
      self.center[i].position += Vehicle_speed

  index_removal.reverse()
  for i in index_removal:
    Driver = self.center.pop(i)
    Waiting_time = self.Clock_time - Driver.time_of_arrival
    Load =  len(self.East) + len(self.West) + len(self.South) + len(self.North)
    if self.Events:
      print("Time" + str(Waiting_time))
      print("Load:" + str(Load))
    self.Load.append(Load)
    self.total_num_of_times.append(Waiting_time)
```

```
    self.num_of_departures = self.num_of_departures + 1

def operate_entrances(self):

  East_Clear = True
  South_Clear = True
  West_Clear = True
  North_Clear = True

  for Driver in self.center:
    if Driver.position >= Capacity - Vehicle_speed:
      South_Clear = False

    elif Driver.position >= East - Vehicle_speed and Driver.position < East:
      East_Clear = False

    elif Driver.position >= North - Vehicle_speed and Driver.position < North:
      North_Clear = False

    elif Driver.position >= West - Vehicle_speed and Driver.position < West:
      West_Clear = False

  if South_Clear and len(self.South) > 0:
    self.center.append(self.South.pop(0))

  if East_Clear and len(self.East) > 0:
    self.center.append(self.East.pop(0))

  if West_Clear and len(self.West) > 0:
    self.center.append(self.West.pop(0))

  if North_Clear and len(self.North) > 0:
    self.center.append(self.North.pop(0))
```

```python
def arrival_generate(self):
  w = random.random()
  Vehicles_per_second = 1/Mean_Arrival_Time
  if Vehicles_per_second <= 1 and w < Vehicles_per_second:
    self.driver_generate()
  elif Vehicles_per_second > 1:
    for m in range(round(2*Vehicles_per_second*w)):
      self.driver_generate()

def driver_generate(self):
  e = random.random()
  f = random.random()
  direction_of_arrival = -1
  direction_of_departure = -1

  if f < 0.25:
    direction_of_departure = South
  elif f < 0.5:
    direction_of_departure = East
  elif f < 0.75:
    direction_of_departure = North
  else:
    direction_of_departure = West

  if e < 0.25:
    direction_of_arrival = South + 1
    self.South.append(Driver(self.clock_time, self.clock_time, direction_of_arrival, direction_of_departure))

  elif e < 0.75:
    direction_of_arrival = North + 1
    self.North.append(Driver(self.clock_time, self.clock_time, direction_of_arrival, direction_of_departure))

```

```python
  elif e < 0.5:
    direction_of_arrival = East + 1
    self.East.append(Driver(self.clock_time, self.clock_time, direction_of_arrival, direction_of_departure))

  else:
    direction_of_arrival = West + 1
    self.West.append(Driver(self.clock_time, self.clock_time, direction_of_arrival, direction_of_departure))

def stats_of_printing(self):
  print("[North, South, East, West, Center] = [" + str(len(self.North)) + "," + str(len(self.South)) + "," + str(len(self.East)) + "," + str(len(self.West)) + "," + str(len(self.Center)) + "]")

def report_generate(self):
  print()

def average(l):
  return sum(l)/len(l)
```

Figure 5: Code for simulation at Intersection

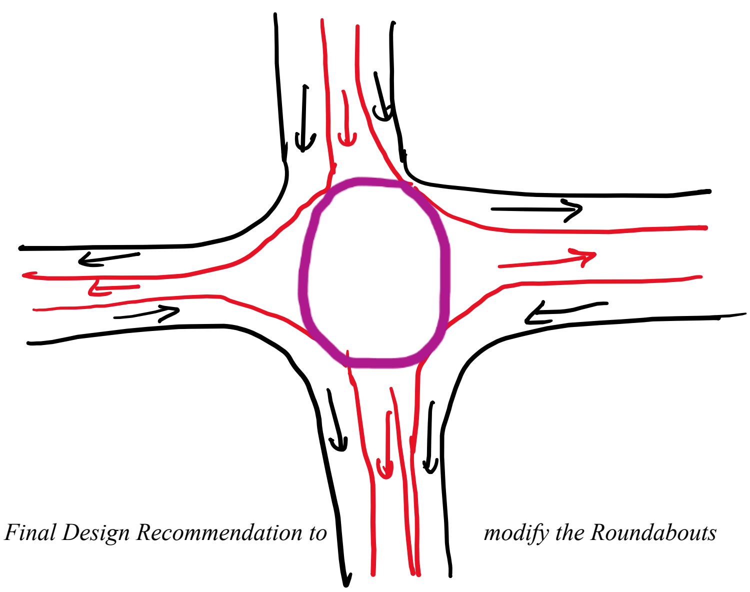

Figure 6: Final Design Recommendation to modify the Roundabouts