



Daniel Sumann, BSc

# **Method of Hyperparameter Optimization of a Genetic Algorithm applied in Critical Scenario Generation for Autonomous Vehicles**

## **Master's Thesis**

to achieve the university degree of

Master of Science

Master's degree programme: Computer Science

submitted to

**Graz University of Technology**

Supervisor

Univ.-Prof. Dipl.Ing. Dr.techn. Franz Wotawa

Institute for Softwaretechnology

Head: Univ.-Prof. Dipl.Ing. Dr.techn. Franz Wotawa

Seiersberg-Pirka, December 2023

This document is set in Palatino, compiled with pdf $\text{\LaTeX}2\text{e}$  and Biber.

The  $\text{\LaTeX}$  template from Karl Voit is based on KOMA script and can be found online: <https://github.com/novoid/LaTeX-KOMA-template>

---

## Affidavit

I declare that I have authored this thesis independently, that I have not used other than the declared sources/resources, and that I have explicitly indicated all material which has been quoted either literally or by content from the sources used. The text document uploaded to TUGRAZonline is identical to the present master's thesis.

---

Date

---

Signature



# **Abstract**

This is a placeholder for the abstract. It summarizes the whole thesis to give a very short overview. Usually, this the abstract is written when the whole thesis text is finished.



# Contents

<b>Abstract</b>	<b>v</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Research Questions . . . . .	2
1.1.1 Research Question 1 . . . . .	2
1.1.2 Research Question 2 . . . . .	3
<b>2 Foundations</b>	<b>5</b>
2.1 Genetic Algorithm . . . . .	5
2.1.1 Chromosomes and Genes . . . . .	7
2.1.2 Population Size . . . . .	8
2.1.3 Selection . . . . .	8
2.1.4 Crossover . . . . .	10
2.1.5 Mutation . . . . .	11
2.1.6 Adaptive Control Parameters . . . . .	11
2.2 Behaviour Tree . . . . .	12
2.2.1 Control Flow and Execution Nodes . . . . .	13
<b>3 Implementation</b>	<b>15</b>
3.1 Traffic Manager . . . . .	15
3.1.1 Action Interface . . . . .	15
3.2 Genetic Algorithm . . . . .	17
3.2.1 Maximum Number of Generations . . . . .	17
3.2.2 Encoding . . . . .	18
3.2.3 Cost Function . . . . .	22
3.3 Behaviour Tree . . . . .	23
3.3.1 Structure . . . . .	23

## Contents

---

<b>4 Hyperparameter Tuning</b>	<b>25</b>
4.1 Simulation Setup . . . . .	25
4.2 Population . . . . .	26
4.2.1 Suggested Hyperparameter from the Literature . . . . .	27
4.2.2 Comparison of Population Size . . . . .	28
4.3 Design of Experiment . . . . .	28
4.3.1 Taguchi Method . . . . .	30
4.3.2 Selection of a Suitable Standard Orthogonal Array . . . . .	33
4.3.3 Result Analysis . . . . .	36
<b>5 Evaluation</b>	<b>49</b>
5.1 Start Scenario 1 . . . . .	50
5.2 Start Scenario 2 . . . . .	51
5.3 Start Scenario 3 . . . . .	53
5.4 Start Scenario 4 . . . . .	54
<b>6 Conclusion</b>	<b>57</b>
6.1 Research Questions . . . . .	57
6.1.1 Research Question 1 . . . . .	57
6.1.2 Research Question 2 . . . . .	58
6.2 Outlook and Future Work . . . . .	58
6.2.1 Additional Actions . . . . .	58
6.2.2 Oracles . . . . .	59
<b>Bibliography</b>	<b>61</b>
<b>Appendix A.</b>	<b>69</b>
<b>Appendix B.</b>	<b>71</b>

# List of Figures

3.1	Action Interface Structure . . . . .	17
3.2	Time . . . . .	19
3.3	Time + NPC . . . . .	19
3.4	Implemented Behaviour Tree . . . . .	24
4.1	mean and error bars per population size . . . . .	29
4.2	Linear Graph of $L_{16}(2^{15})$ taken from Yang and El-Haik, 2009 .	35
4.3	Modified Linear Graph to fit our needs . . . . .	36
4.4	Percentage Contribution . . . . .	41
4.5	Main Effects . . . . .	42
4.6	Test of interactions . . . . .	43
4.7	Elite Selection Comparison . . . . .	46
4.8	Comparison Elite Selection vs No Elite Selection . . . . .	47
5.1	Start Scenario 1: Default GA vs Optimized GA vs Random Search . . . . .	50
5.2	Start Scenario 1: Comparison of GAs . . . . .	51
5.3	Start Scenario 2: Default GA vs Optimized GA vs Random Search . . . . .	52
5.4	Start Scenario 2: Comparison of GAs . . . . .	52
5.5	Start Scenario 3: Default GA vs Optimized GA vs Random Search . . . . .	53
5.6	Start Scenario 3: Comparison of GAs . . . . .	54
5.7	Start Scenario 4: Default GA vs Optimized GA vs Random Search . . . . .	55
5.8	Start Scenario 4: Comparison of GAs . . . . .	55
1	Start Scenarios . . . . .	69
2	Start Scenarios . . . . .	70



# List of Tables

3.1	Probability of Actions for Actors . . . . .	20
3.2	Integer Encoding: Probability of Parameters per Action . . . . .	21
3.3	Dictionary Encoding: Probability of Parameters per Action . . . . .	22
4.1	Summary of Genetic Algorithm Hyperparameters . . . . .	27
4.2	results from testing population size - mean of 5 repetitions . . . . .	28
4.3	Control Parameters (Factors) with corresponding Settings (Levels) - (*uniform) . . . . .	33
4.4	$L_{16}(2^{15})$ Taguchi orthogonal array taken from Roy, 1990 . . . . .	34
4.5	Rules taken from Roy, 1990 . . . . .	35
4.6	Building 4 Level columns from 2 Level columns . . . . .	37
4.7	Final version of used Taguchi orthogonal array . . . . .	38
4.8	ANOVA results . . . . .	39
4.9	S/N ANOVA results . . . . .	45
1	Hyperparameter Tuning: Taguchi Experiment Results . . . . .	71
2	Evaluation Results Optimized . . . . .	72
3	Evaluation Results Default . . . . .	72
4	Evaluation Results Random . . . . .	72



# 1 Introduction

Automated driving has made considerable advancements in the last 15 years, yet significant technical challenges still persist (Ayoub et al., 2019). Fully developed and integrated, it will have a lasting impact on mobility, road safety as well as society in general (Milakis, Van Arem, and Van Wee, 2017).

Different complexity levels of driving automation are defined by the Society of Automotive Engineers (SAE)SAE International, 2021 with a level 5 system being required to perform the entire task of driving completely without a human driver. Lower levels take over only parts of the driving, such as parking, steering, etc ... Examples are driver support features such as Automatic Emergency Braking (AEB) or Automatic Lane Keep Systems (ALKS).

Automated driving systems are considered safety-critical and need responsible and throughout testing in order to minimize traffic accidents and human harm. According to Klück, 2022, the main requirements of automated driving systems are that they "must operate under all circumstances" and, that these systems "must be safe". Self-driving systems have the potential for harm, as their failure may lead to catastrophic accidents. Due to the complexity of the environment, in which automated driving systems are applied, high quality testing is needed.

*"Thoroughly validating and verifying automated or autonomous driving functions is inevitable for assuring to meet quality criteria for safety-critical systems." (Felbinger et al., 2019)*

According to Kalra and Paddock, 2016, a huge amount of miles driven by an autonomous driving system is required to demonstrate and test their statistical safety compared to human driving. Accumulating this amount

might not be feasible by driving in the real world. Klück, 2022 adds, that unguided mileage collection may provide only "limited quality assurance". During real world driving, the number of challenging situations is low, as most everyday situations can be driven without trouble.

According to Klück, 2022, search based testing (SBT) is a possible tool for improving the robustness and revealing systematic failures of automated driving systems. SBT generates inputs for a system under test in order to trigger some unwanted behaviour. It utilizes a problem-specific cost function that guides the search towards areas that have a high probability of failures. SBT can be applied to complex and large search spaces, where other, less focused, testing tools like full factorial or random testing might struggle. Genetic algorithms (GAs) are a viable tool of search based testing and were already successfully utilized in the domain of automated driving, as evidenced by notable studies such as Klampfl, Klück, and Wotawa, 2023, Felbinger et al., 2019, Kaufmann et al., 2021 and Almanee et al., 2021. This thesis will use a genetic algorithm in order to generate critical driving scenarios for testing self-driving technology in vehicles. While generating these scenarios is the objective, the main task of the thesis will evolve around the implementation of the genetic algorithm as well as the optimization of its hyperparameters.

## 1.1 Research Questions

The following two research questions will provide a guideline for this master's thesis. Both questions evolve around examining and comparing the performance of a genetic algorithm on generating critical scenarios for autonomous vehicles. The actual cost function is explained in Chapter 3.

### 1.1.1 Research Question 1

*Is a genetic algorithm suitable for generating critical driving scenarios compared to random search?*

## 1.1 Research Questions

---

Although the (in the previous Section) presented papers provide strong suggestions that a genetic algorithm has a significant advantages over random search, a comparison is still highly important. Are situations possible, where a genetic algorithm struggles to find critical scenarios compared to a random approach?

### 1.1.2 Research Question 2

*Is it possible to improve the performance of a genetic algorithm by optimizing the control parameter using the taguchi method?*

In order tune the hyperparameter of the genetic algorithm, design of experiment, specifically the taguchi method was used. In an effort to test, if significant performance improvements are possible, the optimized GA will be compared to a GA using control parameters as recommended by existing literature. This evaluation aims to understand, whether notable performance advancements for genetic algorithms are possible by deploying this method.



# **2 Foundations**

## **2.1 Genetic Algorithm**

Pioneered by Holland, 1992, genetic algorithms imitate the process of natural selection and the darwinian principle called "survival of the fittest". Genetic algorithms are a subclass of evolutionary algorithms (EAs) and explore the solution space using a population of individuals (Mills, Filliben, and Haines, 2015). Each individual contains one chromosome, which serves as a candidate solution. Using genetic operations, the individuals mate among themselves and mutate independently.

The selection of an individual is determined by a fitness function, which defines the search problem. Each individual has a fitness value corresponding to the performance of its chromosome (Majumdar and Ghosh, 2015). Individuals that do poorly on the given problem die out, while individuals deemed "strong" propagate. Genetic algorithms optimize iteratively, with each iteration referred to as a generation. Chromosomes consist of individual genes, which form a solution to the search problem. Through successive generations using genetic operations, gene values and position will be optimized, resulting in progressively improved solutions (Srinivas and Patnaik, 1994). Generational genetic algorithms, where the entire population is replaced each generation, will be utilized in this master's thesis. In contrast, steady state genetic algorithms only replace a small fraction of the population at a time (Srinivas and Patnaik, 1994).

This search method on the basis of biological principles allows for a global and dispersed search through its population, which avoids various shortcomings of local search techniques (Grefenstette, 1986). Especially on challenging search spaces with multiple local optima, a GA is less prone to get stuck on a substandard solution (Katoch, Chauhan, and Kumar, 2021, Xia et al., 2019,

## 2 Foundations

---

Majumdar and Ghosh, 2015). Genetic algorithms offer advantages for complex optimization and non-deterministic polynomial (NP-hard) problems (Hussain and Muhammad, 2020).

*"GAs can find good solutions within a large, ill-defined search space, and can be readily adapted to a wide variety of search problems" (Mills, Filliben, and Haines, 2015)*

Grefenstette, 1986 further emphasizes its ability to outperform gradient techniques on difficult problems with high-dimensional, noisy or discontinuous fitness functions by efficiently exploiting a "relatively simple selection mechanism." The main advantage of a GA in tackling these problems comes from its capability to explore the search space using its entire population (Hussain and Muhammad, 2020). The "high implicit parallelism" makes genetic algorithms "numerically very efficient" (Marsili Libelli and Alba, 2000). A basic GA proposed by Holland, 1992 can be defined as follows:

```
1 simple_genetic_algorithm()
2 {
3     initialize_population();
4     evaluate_population();
5     for(int i = 0; i < num_of_generations; i++)
6     {
7         select_individuals_for_next_population();
8         perform_crossover();
9         perform_mutation();
10        evaluate_population();
11    }
12 }
```

The population is initialized randomly, and its individuals are subsequently evaluated using the fitness function. The following steps are iteratively repeated until some stopping criterium is triggered. The individuals are chosen using a selection operation, which takes their fitness value under consideration. A crossover rate subsequently determines which individuals mate using a crossover function. This operation serves the purpose of exchanging information between the chromosomes. In order to add variation and diversity, the resulting crossover offspring undergoes small changes using a mutation function. A mutation rate decides on which individuals

this operation is applied. The newly generated population will then get evaluated for the next iteration. Different stopping methods like time limit, fitness limit, minimum convergence rate or maximum number of generations are available (Majumdar and Ghosh, 2015).

As discussed by Hussain and Muhammad, 2020, genetic algorithms suffer from an exploration vs exploitation dilemma. If the algorithm converges too quickly to a solution, most of the search space might not have yet been explored, thus increasing the probability of getting stuck in a local optimum. In contrast to that, a low convergence rate might be time consuming and result in inefficient utilization of computational resources.

*“Finding a balance between exploration and exploitation has been a difficult-to-achieve goal from the beginning.” (K. De Jong, 2007)*

Achieving this balance requires a suitable choice on both genetic functions as well as on their applied probabilities. Due to no real consensus on the best control parameter settings, their optimal selection proves to be difficult (K. De Jong, 2007).

### 2.1.1 Chromosomes and Genes

Both chromosomes as well as genes require adequate encodings in order to fit the search task. Each chromosome, existing of a list of genes, needs to represent a complete solution of the specific problem. Finding suitable encodings proved to be, besides the hyperparameter tuning, the main challenge of setting up a genetic algorithm pipeline.

While the chromosome encoding is very problem specific and heavily depends on the choice of gene encoding, there are various gene encodings suggested by the literature. A simple and commonly used representation for genes is binary encoding, where a gene can take on the form of 0 or 1. Further common encodings are octal and hexadecimal representations (Srinivas and Patnaik, 1994, Katoch, Chauhan, and Kumar, 2021). Srinivas and Patnaik, 1994 further suggests integer representations in case a optimization problem has real-valued continuous variables, where the objects are linearly mapped to integers defined in a specific range. It is possible to

again represent these integers as binary encodings. Various other encodings are available, often very problem specific. For example tree encodings allows for genes to represent programming functions, leading to a subcategory of genetic algorithms called "genetic programming" (Katoch, Chauhan, and Kumar, 2021). In case no gene encodings fits the given problem, a custom encoding can be used. Here the genetic operation crossover and mutation might have to be tailored accordingly.

### 2.1.2 Population Size

Setting the population size, which defines the number of individuals per generation, has a direct impact on the performance of a genetic algorithm. Increasing the population size will increase the degree of parallelism in the genetic algorithm, as each individual represents one search point (Mills, Filliben, and Haines, 2015).

Research seems to be in agreement, that a small population leads to less diverse individuals and might provide an insufficient sample size, which can lead to a premature convergence to a local optimum. A large population size will allow the GA to perform a more informed search. However computation time will suffer due to the larger number of individuals per generation and might lead to slower convergence to an optimum (Grefenstette, 1986, Katoch, Chauhan, and Kumar, 2021, K. De Jong, 2007).

### 2.1.3 Selection

The selection operator chooses two parents for crossover and mutation operations until the list of offsprings has reached the desired population size. Individuals are chosen based on their fitness value, ensuring their increased representation from generation to generation. Weak solutions will be discarded over time (Srinivas and Patnaik, 1994). The selection algorithm needs to satisfy two requirements. On the one hand, high selection pressure will lead to decreased diversity in the population resulting in premature convergence (Katoch, Chauhan, and Kumar, 2021). The algorithm will subsequently behave more like a local search method, a hill-climber

## 2.1 Genetic Algorithm

---

or a greedy algorithm (K. De Jong, 2007). The initial low average fitness value of the population will in combination with a few good performing individuals lead to them overtaking the population, drastically reducing diversity. On the other hand, a low selection pressure will struggle to converge to an optimum. Different selection methods like Stochastic Uniform Remainder, Random Selection, Rank Selection, Roulette Wheel Selection and Tournament Selection exist (Majumdar and Ghosh, 2015). According to Hussain and Muhammad, 2020, who provide a extensive comparison of different selection techniques, the choice of selection methods highly affects the performance of the genetic algorithm.

Roulette wheel selection is a popular mechanism, where each individual corresponds to an area on a roulette wheel, based on its fitness value (Holland, 1992). Grefenstette, 1986 points out the scaling problem as its major drawback. As the algorithm progresses, its fitness variance to mean ratio becomes increasingly small, leading to low selection pressure. This problem can be mitigated by using ranks instead of the fitness value (Katoch, Chauhan, and Kumar, 2021). Individuals will be sorted based on their performance, their relative rank is inserted into the roulette wheel instead.

Tournament selection is a popular alternative to roulette wheel selection. First, a tournament size  $t$  has to be chosen. Until the desired number of offsprings is achieved,  $t$  individuals will be chosen at random from the population. Only from this smaller list, the best individual is selected. A popular tournament size is 2, larger sizes might enhance competition among individuals, however they can also has an impact on the diversity of the population (Hussain and Muhammad, 2020). In a comparison of different selection methods by Jinghui Zhong et al., 2005, tournament selection was deemed to be the most performant, converging more quickly then for example roulette wheel selection.

Elite selection is an additional method which can enhance a selection operation and was proposed by K. A. De Jong, 1975. The best  $n$  individuals are automatically chosen for the next generation. Elite selection can help reduce variance, as the highest performing individuals can not be removed by randomness.

### 2.1.4 Crossover

The crossover operation serves as the mating process between two individuals (chosen from the population by the selection operation). Its resulting offspring is a combination of both parent genes. Grefenstette, 1986 highlights, that first, “it provides new points for further testing within the hyperplanes already represented in the population” and second, that “crossover introduces representatives of new hyperplanes into the population”.

Different types of crossovers can be implemented, the most simple approach being the single-point crossover. Here a point is chosen at random along the length of the chromosome. The two parents will swap their genetic information at this position, generating two new offsprings (Katoch, Chauhan, and Kumar, 2021). Extension are the two- or multipoint crossover operations, where chromosomes are divided by  $k$  segments, which will get exchanged. They eliminate a disadvantage of “the single-point crossover bias toward bits at the ends of strings” (Srinivas and Patnaik, 1994). A second crossover operation is the uniform crossover where gene swaps between parents are randomly decided by a given probability, independent to the exchange of other genes (Katoch, Chauhan, and Kumar, 2021). Various other crossover operations are shown in paper University Malaysia of Computer Science and Engineering et al., 2017.

Srinivas and Patnaik, 1994 proposed the notion of positional and distributional bias. If a crossover operation has a positional bias, the probability of a bit to be swapped depends mainly on its position. Examples are the mentioned single and multipoint crossover operators. The uniform crossover can be found at the other end of the spectrum, as it has a maximal distributional bias, completely disregarding any positional information. Ignoring the gene positions results in a higher disruptiveness, which has potential drawbacks. However it will be more exploratory in homogeneous populations where  $k$ -point crossovers might struggle. Srinivas and Patnaik, 1994 suggest that uniform crossover is more useful in small populations. Larger populations inherently are more diverse, making  $k$ -point crossover more suitable.

Not only the crossover type has to be chosen, a crossover rate also needs a declaration. This value defines, how likely a single crossover operation is to

be applied on the selected individuals. Choosing a suitable crossover probability is again influenced by the exploration-exploitation balance. Higher crossover rates will introduce new structures quickly into the population, however good sequences of genes might get disrupted. A low crossover rate will result in a low exploration which leads to stagnation (Grefenstette, 1986).

### 2.1.5 Mutation

The mutation operation is applied after crossover as a means to maintain the diversity of the gene pool. Through small random changes, the variability of the population increases. Each individual can be exposed to mutation, irrespective of their fitness value. A mutation rate chooses the individuals to be mutated. An additional individual mutation rate selects which specific genes of the chosen chromosome are mutated (Srinivas and Patnaik, 1994). Depending on the gene encoding, the mutation operation might vary. In case of binary gene encoding, mutation will only flip certain bits. For custom encodings, the mutation operation needs to be tailored accordingly.

*“If the mutation is not considered during evolution, then there will be no new information available for evolution.”*(Katoch, Chauhan, and Kumar, 2021)

The settings for mutation rates again needs to be chosen carefully. If they are set too high, the genetic algorithm might transform into random testing. In case they are set too low, the population will not be able to maintain diversity as no new genetic material is reintroduced. (Klampfl, Klück, and Wotawa, 2023, Grefenstette, 1986).

### 2.1.6 Adaptive Control Parameters

Various literature suggests adaptively controlling selection methods, crossover rates and mutation rates over the duration of a genetic algorithm (Marsili Libelli and Alba, 2000, ). The main goal is to mitigate the previously mentioned exploration-exploitation problem. In the beginning, exploration is

insert papers

desired, thus low selection pressure as well as high crossover and mutation rates are required. However to the end of the genetic algorithms duration, convergence to an optimum is preferred, meaning more "elite" selection methods as well as less variation due to crossover and mutation (Srinivas and Patnaik, 1994).

Marsili Libelli and Alba, 2000 proposed a method, where different mutation rates are used depending on the fitness of the individual. They claim, that a higher mutation probability for low fitness population results in a more efficient search. Hussain and Muhammad, 2020 argue for a selection operation, where initially a low selection pressure is applied while increasing it to the end, stating that this approach will help mitigate both mentioned competing criteria, namely premature convergence as well as slow convergence.

Contrary, K. De Jong, 2007 is more critical on adaptive control parameters. Although adaptive control parameter might improve the performance of a genetic algorithm for specific problems, genetic algorithms are already quite robust in practice. Adding more tunable parameters will not make the task of the researcher easier.

*"The purist might argue that inventing feedback control procedures for EAs is a good example of over-engineering an already sophisticated adaptive system." (K. De Jong, 2007)*

K. De Jong, 2007 adds, that "after more than 30 years of experimenting with dynamic parameter setting strategies, is that, with one exception, none of them are used routinely in every day practice. The one exception are the strategies used by the ES community for mutation step size adaptation." In order to keep the number of tunable parameters low, the approach implemented by this master's thesis will not utilize adaptive control parameters.

## 2.2 Behaviour Tree

Behavior Trees were invented and developed by the computer game industry as a control structure of non-player characters (Collendanchise and Ögren,

2019). Since then, their scope of application has expanded into various application fields, including robotics, smart homes, power grids, autonomous vehicles (Iovino et al., 2022). Sprague et al., 2018 show, that they can also be used as a robust control architecture for autonomous underwater vehicles. A behavior tree is a directed tree, with root, child, parent and leaf nodes. Non-leaf nodes are control flow nodes, while leaf nodes are called execution nodes. The execution of a BT is done by ticks, that propagate down starting from the root node with a given frequency to its children. All nodes only execute when receiving a tick and can return either "Running", "Success" or "Failure" (Collendanchise and Ögren, 2019).

Their high modularity and reactivity are often stated as their main advantages. The high modularity stems from the fact, that different parts in the BT can be changed and modified without influencing the rest of the tree. This goes in hand with the reactivity shown by the Behavior Tree. Per tick, safety test can be performed before going into the execution logic of the tree, making the system react immediately to a non safe situation. Adding complex details to this execution sub-tree will not jeopardize with the safety tests (Sprague et al., 2018).

### 2.2.1 Control Flow and Execution Nodes

The control flow nodes decide which actions and condition nodes to execute next. Three categories of control flow nodes (Sequence, Fallback and Parallel) exist. The two existing categories of execution nodes are actions and conditions, both are responsible for executing the actual behavior of the behavior tree. (Collendanchise and Ögren, 2019).

- Control flow nodes
  - **Sequence nodes** will execute its children nodes (routing the ticks) in sequence as long as each child returns "Success". If this has happened for every child, the sequence node itself will return "Success". In case one child returns "Failure" or "Running", the sequence node will immediately return the corresponding value and not route the tick to the next child.

- **Fallback nodes** executes its children one after another until one child returns "Success" or "Running", in which case it will itself returns "Success" or "Running" accordingly. As long as the childs status is "Failure", it will continue routing the ticks to the next child. If all children have returned "Failure", the fallback node will also return "Failure".
  - **Parallel nodes** will execute all children simultaneously. Given a parameter m, it will decide on its return status. If more than m children succeeded, it will return "Success". If enough children have failed to make the "Success" impossible, "Failure" is returned, otherwise "Running".
- Execution nodes
    - **Action nodes** will execute a command after receiving a tick. They can return "Success", "Failure" as well as "Running". Action nodes typically execute the behavior of an agent, for example: "open door".
    - **Condition nodes** will execute a command after receiving a tick. However contrary to the Action Nodes, the can only return "Success" and "Failure". It is not possible for them execute over multiple ticks and thus can not return "Running". As suggested by their name, Condition Nodes typically check conditions like for example: "is door closed".

# 3 Implementation

## 3.1 Traffic Manager

A custom developed Traffic Manger will be used to simulate an traffic environment, which can subsequently be controlled by the Genetic Algorithm. The Traffic Manager is not part of the master's thesis and will be regarded as a "blackbox", only receiving a brief introduction. Generally speaking, it will simulate traffic using a start scenario, in which the positions and types of actors (vehicles and pedestrians) are defined. For all simulations done by this thesis, the Traffic Manager was set to 100Hz and the simulation duration set to 35 seconds.

A simulation always consist of at least one EGO vehicle. Additionally any number of NPCs can be added. The EGO vehicle can be either partly or completely supervised by autonomous driving functions. The goal of the genetic algorithm is subsequently to test this function for safety, comfort etc... by controlling the NPCs in order to generate critical scenarios.

### 3.1.1 Action Interface

In order to control the behaviour of all actors inside the simulation, actions can be requested over the Action Interface, which is provided by the Traffic Manager. An action will initiate a certain behaviour from an actor and can be set at any timestep<sup>1</sup>. Pedestrians and vehicles have a different set of possible actions. If no action is applied, the actor will behave in a normal

---

<sup>1</sup>depending on the autonomous driving function under test, the Action Interface might be disabled for the EGO vehicle

### 3 Implementation

---

manner inside the simulation. This means that the actor will follow along its given path until a new action changes its behaviour.

The following list shows all actions provided by the traffic manager which were available for the genetic algorithm at the time of this master's thesis.

- JunctionSelection
  - vehicle\_id: int, step: int, junction\_selection\_angle (radians): float
  - Vehicles will chose which direction to take at junctions based on this angle.
- LaneChange
  - vehicle\_id: int, step: int, direction: float, distance: float, delay (optional): float
  - Initiates a lane-change based on its given parameters.
- AbortLaneChange
  - vehicle\_id: int, step: int
  - Will abort a current lane-change.
- ModifyTargetVelocity
  - vehicle\_id: int, step: int, percentage: float
  - Modifies the internal target velocity of the vehicle by a percentage.  
If set to 0, the vehicle will stop.
- TurnHeading
  - pedestrian\_id: int, step: int
  - The pedestrian will turn 180 degrees and walk in the opposite direction
- CrossRoad
  - pedestrian\_id: int, step: int
  - The pedestrian will cross the road immediately.
- CrossAtCrosswalk
  - pedestrian\_id: int, step: int
  - The pedestrian will cross the road at the next crosswalk.

## 3.2 Genetic Algorithm

The genetic algorithm will control only NPCs, a behaviour tree is used for the EGO vehicle itself. Both methods use the Action Interface to control their respective actors. An overview is provided in Figure 3.1.



Figure 3.1: Action Interface Structure

## 3.2 Genetic Algorithm

The genetic algorithm will search for sequences of actions that will result in the most interesting scenarios according to its cost function. For implementing the genetic algorithm, the Python library DEAP<sup>2</sup> was chosen. It is a popular tool in academia and allows for high customisability. The algorithm has full access over the setting of actions for all NPCs. Searching for sequences of actions, the GA tries to optimize a cost function.

A few default settings for the genetic algorithm were chosen. It was decided for example, that the genetic algorithm will be able to set an action per actor every 50 steps, which translates to 0.5 seconds (simulation runs at 100hz). In other words, every 50 steps of the simulation is 1 timestep for the genetic algorithm. If the GA decides to not set an action, "NoAction" will be used as a placeholder.

### 3.2.1 Maximum Number of Generations

A fixed maximum number of generation is a commonly used stopping criteria. While more complex methods like a "adaptive convergence rate" might lead to better performance, it was decided that the additional complexity

<sup>2</sup><https://deap.readthedocs.io/en/master>

of having to choose a suitable convergence rate outweighs its potential benefits. Especially considering that a genetic algorithm already has a lot of different control parameters that need tuning. Performance is always a big consideration in this thesis, thus a lower maximum number of generations is preferred. During testing, a generation size of 30 was almost always sufficient and will be used in all of the coming testing.

#### 3.2.2 Encoding

When implementing a genetic algorithm, it is necessary to use an encoding that fits to the problem at hand. Here, each chromosome is required to include all actions of one whole simulation. Due to the deterministic nature of the Traffic Manager, it is sufficient to define a simulation by only the action sequence from a chromosome and the initial state defining start scenario. The different encodings presented in Section 2.1.1 were not directly applicable to the given problem. A custom encoding for both chromosomes and genes needed to be generated.

##### Chromosome

Two different encodings proved to be a good fit. Both use the position of a gene inside the chromosome to define the time step of an action. Which chromosome encoding is the most adequate will be discussed and tested in Chapter 4.

**Time** The first encoding is called "Time". Each gene corresponds to 1 time step (so 1 gene per 0.5 seconds), and needs to contain all actions of all NPCs at this particular moment. A gene is a list of the size of the number of NPCs. Each object in this lists equals an action. The index of an action inside a gene corresponds to the NPC ID. For example, an action positioned in the gene at index 2, will be applied to NPC 2. If the gene is at position 6 in the chromosome, the action will be set at second 3.0 in the simulation. A visualization is seen in Figure 3.2.

### 3.2 Genetic Algorithm

---

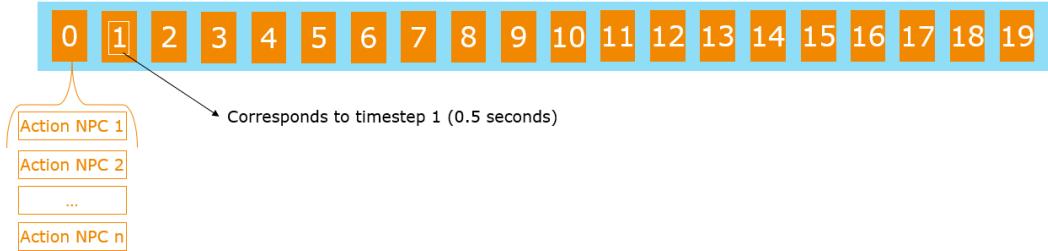


Figure 3.2: Time

Given the previously stated simulation time of 35 seconds, each chromosome has a length of  $35 * 2 = 70$  genes. The crossover operation can only move all actions of a time step at once, modifications in the timeline between actions of the same time step will only happen due to a mutation operation.

**Time+NPC** The second encoding is called Time+NPC. Here, one gene corresponds to exactly one action. In order to not loose required information, the ID of each NPC has to be encoded into the genes position of its chromosome. One might visualize this as unfolding the matrix build by the genes and chromosome in encoding Time into a linear array. Each actors actions will be listed one after another. Now, each gene has a length of 1 and each chromosome has a length of  $35 * 2 * \text{number\_of\_actors}$ , which makes them much longer compared to the previous encoding. Figure 3.3 provides a visualization. In this example, a gene at position 13 corresponds to an action for NPC 2 at time step 3 (which is at 1.5 seconds in the simulation).

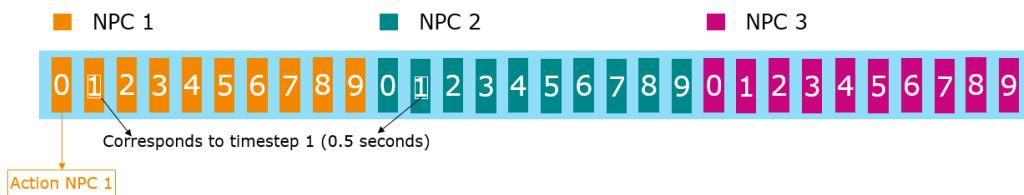


Figure 3.3: Time + NPC

However for this encoding to make sense, the crossover operations OnePoint and TwoPoint had to be modified in a way, that for each NPC, these crossover

### 3 Implementation

---

operations are applied individually. If this was not the case, OnePoint crossover would introduce changes to actions of only one NPC. Because the different crossover points are independently chosen, the position of the crossing now differs between the NPCs. This allows the crossover operation to break up actions at the same time step, which was not possible with the Time encoding.

#### Gene

Two different encodings for genes were implemented. A gene always consists of a list, which depending on the chromosome type either has a length of *number\_of\_actors* (in case of Time) or of length 1 (in case of Time+NPC). The following two encodings thus explain the type of object in these lists. In both encodings, the probability of each action remains the same and can be seen in 3.1.

Vehicles		Pedestrians	
ActionType	Probability	ActionType	Probability
NoAction	65%	NoAction	84%
JunctionSelection	6%	PedTurnHeading	2%
LaneChange	10%	PedCrossRoad	4%
AbortLaneChange	2%	CrossAtCrosswalk	10%
ModifyTargetVelocity	17%		

Table 3.1: Probability of Actions for Actors

These probabilities were manually chosen based on experience. For example setting PedTurnHeading to a high probability will see many pedestrians change their direction in front of the EGO vehicle multiple times, in order to initiate emergency breaks by the EGO.

**Integer** The first encoding uses integer, which are translated into actions when the simulation is started. For each action, a range of integers is assigned, the larger a range, the more likely an action is chosen by the GA. These ranges correspond to the probabilities given in 3.1.

Actions which require parameters need their assigned integer range to be manually split again. For example, it was decided, that `ModifyTargetVelocity` has five different percentage settings, namely 50, 70, 100, 130, 160. So each of these 5 settings needs a unique range of integers assigned, again with different lengths, in order to have different probabilities. A percentage setting of 100 for example has the largest integer range assigned. A complete list can be seen in 3.2.

ActionType	Parameter	Probability
JunctionSelection	straight	34%
	left	33%
	right	33%
LaneChange	left	50%
	right	50%
ModifyTargetVelocity	50	10%
	70	20%
	100	45%
	130	20%
	160	5%

Table 3.2: Integer Encoding: Probability of Parameters per Action

Combining these ranges results in a continuous list of integers. The genetic algorithm will choose integers in the list for its genes. Before a simulation is started, these integers are encoded back into actions.

**Dictionary** The second encoding for genes corresponds exactly to the actual actions used in the simulations, requiring no translation. Each action is again selected based on the same probabilities in 3.1. For actions without parameters, the different encoding will make no difference. However actions with parameters are no longer split into different discrete settings. Now, each parameter is chosen by a randomness function, which is individually selected per action. For example in case of the percentage parameter in `ModifyTargetVelocity`, the values are selected from a gaussian distribution with  $\mu=100$ ,  $\sigma=25$  and a range limit between 0 and 300. An overview is provided in Table 3.3. Again, these probability functions were assigned based on intuition as well as trial and error.

### 3 Implementation

---

ActionType	SelectionFunction	Settings
JunctionSelection	Choice	[straight, left, right]
LaneChange	Choice	[left, right]
ModifyTargetVelocity	Gauss Distribution	Mu: 100, sigma: 25

Table 3.3: Dictionary Encoding: Probability of Parameters per Action

Compared to integer encoding, this method allows for much higher granularity when selecting parameters. However because only one action type has a setting, that allows for continuos variables, this difference might be insignificant. The contrast between encodings will likely get more pronounced with an increasing number of implemented actions in the Action Interface. Chapter 4 will investigate, if the performance of a genetic algorithm differs between these two encodings.

#### 3.2.3 Cost Function

This master's thesis only utilized internal values from the Traffic Manager for the cost function. Namely if the ego vehicle has to initiate an emergency break. The emergency break values are booleans stored in a list with a length of  $100 * \text{simulation\_duration\_seconds}$  (because of 100hz). As long as the EGO vehicle has no emergency stop initiated, the cost value will increase. If the emergency break max duration is exceeded, the cost value will increase as well. Only in cases where non of these two conditions are fulfilled, no cost will be added. Emergency break max duration is set to 3 seconds and will apply a penalty in case it is exceeded. This penalty was introduced as it mitigated results, where the ego vehicle is constantly brake-checked<sup>3</sup> by the leading vehicle. The resulting cost values however are a not easy to interpret, thus these numbers are modified using equation 3.1.

$$\text{cummulated\_emergency\_break\_duration} = (3500 - \text{cost}) / 100 \quad (3.1)$$

---

<sup>3</sup>"the unsafe action of applying a car's brakes to dissuade a driver who is following too closely" according to <https://www.dictionary.com/e/slang/brake-check/>

The constant 3500 is chosen to account for the 100hz sampling rate and the duration of 35 seconds. The division by 100 transforms the value into seconds. This value will be used from now on instead. A higher cumulated emergency brake duration is preferable. It is important to consider, that this value might not exactly correspond to the actual cumulated emergency brake duration time from the simulation, due to the penalty which the cost function applies for emergency breaks that last longer than 3 seconds.

## 3.3 Behaviour Tree

The EGO vehicle will be controlled by a behaviour tree, which as implemented using the Python library py\_trees<sup>4</sup>. The general idea is to have an EGO vehicle moving in a relatable manner through the world. It will try to dodge standing or slow moving obstacles.

### 3.3.1 Structure

While the behaviour tree has access to the same Action Interface (described in Section 3.1.1) as the genetic algorithm, it needs a higher level of integration with the Traffic Manager. The genetic algorithm is only interested in the resulting emergency break values, the behaviour tree however needs access to internal functions during the simulation. Conditions like NoObstacle() or LaneChangePossible() execute internal Traffic Manager functions to get needed information on the world around the EGO vehicle. Figure 3.4 shows the behaviour tree implemented.

Each tick, the branch junction selection will first get executed, which will switch between the settings "straight", "left" and "right" every 3 seconds. This serves the purpose of generating more interesting situations, as otherwise the ego vehicle will only move straight. A random junction selection would not be possible, as this would make the simulation not deterministic. While implementing a full navigation system was investigated as well, it was

---

<sup>4</sup><https://py-trees.readthedocs.io/en/release-2.2.x/>

### 3 Implementation

---

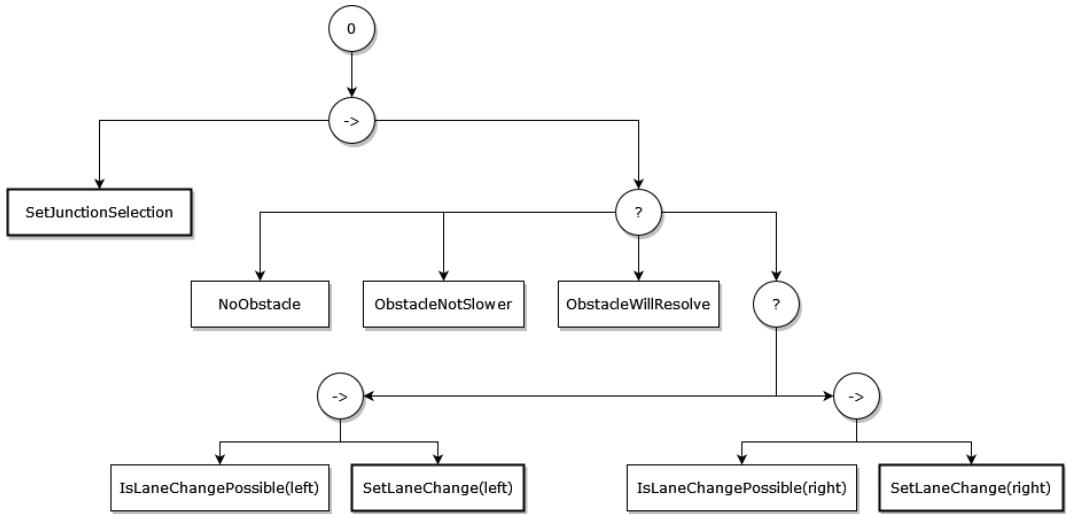


Figure 3.4: Implemented Behaviour Tree

decided against, as the added complexity did not seem to significantly improve the resulting simulations.

The next branch focuses on dodging obstacles. First, the condition `NoObstacle()` decides, if an obstacle is on the path of the EGO vehicle. Second, a threshold of 50% in `ObstacleNotSlower()` declares, if a lanechange makes sense. Third, the `ObstacleWillResolve()` function has the responsibility to check, if the obstacle is 1. in a junction or 2. roughly at a 90 degree angle. In both cases no takeover will be performed. In case all of the 3 functions return false, a final function `LaneChangePossible()` will check, if a lanechange to the left is possible and if this is not the case, if a lanechange to the right is possible. Depending on its result, a lanechange to the suggested direction is performed. `LaneChangePossible()` might not allow a lanechange if 1. there is no lane or 2. if the lane is blocked by an obstacle.

# 4 Hyperparameter Tuning

The performance of a genetic algorithm is significantly influenced by its control parameters. Performant settings on a particular fitness landscape might not be appropriate on a different one (K. De Jong, 2007).

According to the "No Free Lunch Theorem", no single algorithm will outperform all other algorithms on a single class of problem (K. De Jong, 2007). K. De Jong, 2007 further states, that "the No Free Lunch results place an obligation on the EA practitioner to understand something about the particular properties of the problems that (s)he is trying to solve that relate to particular choices of EA parameter settings." A human-in-the-loop approach is needed to fine-tune parameter settings to a particular problem.

explain No Free Lunch Theorem better

This chapter will focus on tuning the genetic algorithm to perform well on the given cost function. First, a choice on the optimal population size is made. Afterwards a Taguchi method is used for tuning the remaining hyperparameter.

## 4.1 Simulation Setup

Two workstations were available for running all of the following simulations. The first workstation had an Intel Core i7-9700K and a GeForce RTX 2070 SUPER with 32 GB of RAM. The second workstation had an Intel Core i7-6850K as well as two Nvidia GeForce GTX 1080 also with 32 GB of RAM. On both systems, Kubuntu 20.04 LTS was the operating system.

As has been defined in chapter 3, each genetic algorithm will run for 30 generations. Additionally 1 simulation will have a duration of 35 seconds. On a single workstation, it takes approximately 3 hours and 50 minutes

## 4 Hyperparameter Tuning

---

to complete one genetic algorithm with a population size of 96. This time indication is however influenced by the number of actors.

Town 10 from the driving simulator Carla<sup>1</sup> will be used as the map for all experiments. It has an adequate size, yet is not too big and allows for interesting manoeuvres.

not sure where  
to show the  
start scenar-  
ios, they are  
currently in the  
appendix

In order to reduce the required number of tests, only one starting scenario was used for all of the tuning of the control parameters. Start scenario 1 can be seen in appendix 1. In chapter 5, the performance of the tuned genetic algorithm on different start scenarios will be investigated.

### 4.2 Population

Finding a suitable population size is of high importance to a genetic algorithm, especially considering the limited processing resources available. On one hand, a population that is too small might result in less diverse runs of the genetic algorithm, on the other hand, if the population size is too high, the simulations will become too costly (see section 2.1).

In order to test for the best population size, other hyperparameters first have to be fixated. While reviewing the literature, trends of general settings for genetic algorithms can be found. Grefenstette, 1986 suggests that a range of control parameter will already lead to acceptable performance, yet optimal performance needs tuning. K. De Jong, 2007 complements these findings, adding that the "sweet spot" for control parameters of genetic algorithms is reasonably large and easy to find. A default set of static parameter values is generally speaking sufficient.

Following this advice, the most suitable population parameters will now be evaluated by fixating the remaining hyperparameters to a small range of suggested values from the literature.

---

<sup>1</sup>[https://carla.readthedocs.io/en/latest/map\\_town10/](https://carla.readthedocs.io/en/latest/map_town10/)

### 4.2.1 Suggested Hyperparameter from the Literature

After reviewing various literature regarding control parameter of genetic algorithms, no clear consensus emerged. Mills, Filliben, and Haines, 2015 come to a similar conclusion, mentioning the inconsistencies between findings during their literature review and highlighting the conflicting evidence regarding "key GA control parameter".

Table 4.1 aims to provide a short, though not exhaustive, overview on different control parameter settings used in the literature. This compilation does not claim to cover the entire scope of available research in this domain, rather it served as a focused effort to identify usable hyperparameters.

Table 4.1: Summary of Genetic Algorithm Hyperparameters

Parameter Set	Pop	Cross	Mut	Sel
K. A. De Jong, 1975	50	0.6	0.001	?
Mills, Filliben, and Haines, 2015	200	?	Adaptive	SUS
Grefenstette, 1986	30	0.95	0.01	?
Grefenstette, 1986	80	0.45	0.01	?
Almanee et al., 2021	50	0.8	0.2	?
Srinivas and Patnaik, 1994	30-100	0.9	0.01	?
Fazal et al., 2005	50	0.5	?	Tourn
Dao, Abhary, and Marian, 2016	200	0.7	?	Roul
Naruka et al., 2019	200	0.4	?	Roul
Jinghui Zhong et al., 2005	50-250	0.1-0.9	0.05-0.25	?

Generally speaking, a low mutation rate is recommended. For example Grefenstette, 1986 suggest poor performance using a rate over 0.05. Using a low mutation rate is also suggested by Whitley, 1994 and Jinghui Zhong et al., 2005. On the other hand, Boyabatli and Sabuncuoglu, 2004 found higher mutation rates for their application to be more suitable. Srinivas and Patnaik, 1994 differentiates between higher and lower population numbers, claiming that a smaller population needs higher mutation rates in order to maintain a sufficient diversity.

analyze other control parameters a bit more

### 4.2.2 Comparison of Population Size

Based on the described research, population sizes of 32, 48, 64 and 96 will be compared. Crossover rates are set to 0.8 and 0.6. For mutation, 0.01 and 0.2 will be discussed. Further, tournament selection of 2 and 4 is used. Individual mutation probability will stay at 0.1. Chromosome encoding is set to Time and gene encoding is set to Integer. Each run will be executed 5 times to reduce randomness and to make the results more robust. Each simulation will last for 30 generations. A list of all settings with the mean over 5 repetitions per population size can be seen in table 4.2.

Settings	Code	32	48	64	96
C: 0.6, M: 0.01, TS: 2	A	4.49	4.84	6.49	6.29
C: 0.6, M: 0.01, TS: 4	B	3.89	4.79	4.21	5.63
C: 0.6, M: 0.20, TS: 2	C	4.38	4.90	4.98	6.69
C: 0.6, M: 0.20, TS: 4	D	4.80	5.33	6.09	6.50
C: 0.8, M: 0.01, TS: 2	E	4.37	6.08	5.29	5.84
C: 0.8, M: 0.01, TS: 4	F	4.48	4.51	4.46	6.03
C: 0.8, M: 0.20, TS: 2	G	4.01	5.60	5.41	6.31
C: 0.8, M: 0.20, TS: 4	H	4.42	4.95	7.06	6.91

Table 4.2: results from testing population size - mean of 5 repetitions

In figure 4.1, the results per population are plotted. The line corresponds to the mean, while the bars show the spread (min to max) of all 5 repetitions.

A higher spread in the results can be seen when looking at small population sizes. Considering these findings, a population size of 96 was chosen. While such a high value will result in a performance impact, it was deemed to be more important to keep the variation low.

explain decision  
a bit more

## 4.3 Design of Experiment

This section aims to find optimal settings for the remaining control parameters of the given problem. Following the conclusion from the previous section 4.2, a population size of 96 will be fixated.

### 4.3 Design of Experiment

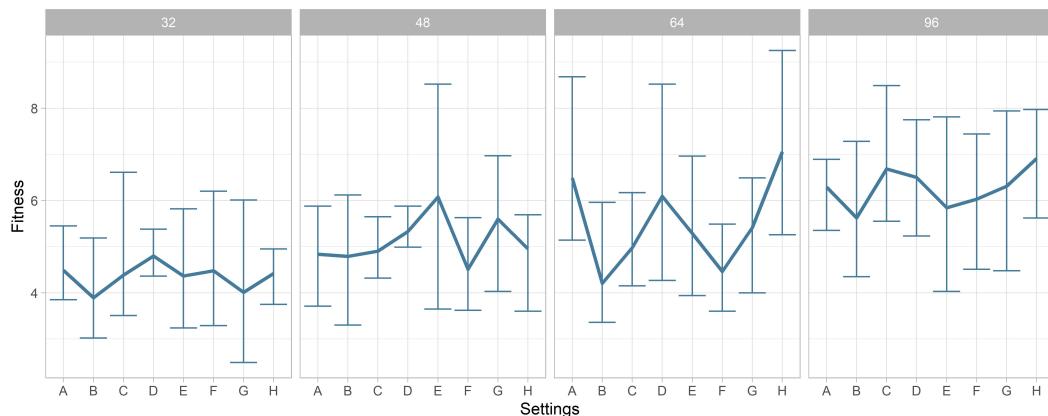


Figure 4.1: mean and error bars per population size

In order to tune the control parameter of the genetic algorithm, various different strategies can be used. Using automated approaches like "grid search", "bayesian optimization", "simulated annealing" or "hyperband" might lead to good results with minimal effort (tuning of hyperparameter for these search algorithms is still needed), however they each require a high number of runs (K. De Jong, 2007). K. De Jong, 2007 even suggest using a second, higher level genetic algorithm for the optimization process.

find more references

Due to performance considerations, many optimization methods did not fit the requirements. Executing one run for 30 generations currently takes around 3:50 hours. The high variance, between runs requires a certain number of repetitions for each setting. Although two different workstations were available, the time required to execute the needed number of runs for these automated tests would exceed the available time budget. For this section, 8 repetitions were used per setting, which makes one evaluation last 30 hours.

A different approach is called design of experiment (DOE), also known as statistically designed experiments. DOE tries to find the cause-and-effect relationship between the factors and the output of experiments. It uses factorial design where the variables in an experiment are named 'factors'. Each factor consists of at least two settings, with the actual number of settings being called 'levels' (Yang and El-Haik, 2009). Design of experiment

## 4 Hyperparameter Tuning

---

needs manual expertise to define which factors are possibly of importance and which settings each factor should have.

*"If the range of variable is too small, then we may miss lots of useful information. If the range is too large, then the extreme values might give infeasible experimental runs." (Yang and El-Haik, 2009)*

Afterwards, main effects and interactions can be calculated to find the best settings per factor. Using ANOVA (Analysis of Variance) it is possible to identify the significance of each factor and interaction, which enables their ranking. More details on these analysis tools will be provided in section 4.3.3.

A full factorial design will test over all possible combinations of the manually selected factor levels. Looking at the proposed factors in table 4.3.1, 1024 runs<sup>2</sup> are required, which not feasible performance wise. A full factorial design has the drawback, that as the number of factors k gets increased, the number of needed experimental runs increases exponentially, thus resulting in lengthy experiments. Yang and El-Haik, 2009 state, that most of the results obtained by testing over all combinations are only used for estimating higher-order interactions, which are in most cases insignificant.

Add Short explanation

Fractional factorial experiments require less runs ...

*"Techniques such as fractional (or partial) factorial experiments are used to simplify the experiment. Fractional factorial experiments investigate only a fraction of all possible combinations. This approach saves considerable time and money but requires rigorous mathematical treatment, both in the design of the experiment and in the analysis of the results." (Roy, 1990)*

### 4.3.1 Taguchi Method

Various improvements to design of experiment have been put forward by Dr. Genichi Taguchi, such as reducing the influence of uncontrollable (noise)

---

<sup>2</sup>number of runs calculated using: <https://datatab.net/statistics-calculator/design-of-experiments>

### 4.3 Design of Experiment

---

factors on processes and products and reducing variability (Roy, 1990). This master's thesis will not discuss all of Taguchi's proposed considerations, for more detail Roy, 1990 as well as Yang and El-Haik, 2009 are recommended.

Taguchi's proposed experimental design is a fractional factorial design, that requires significantly less runs. While different fractional factorial designs are available, Taguchi was chosen, because he provides a simple and easy to follow procedure which requires only a minimal number of runs.

*"There are many similarities between "regular" experimental design and Taguchi's experimental design. However, in a Taguchi experiment, only the main effects and two-factor interactions are considered. Higher-order interactions are assumed to be non-existent. In addition, experimenters are asked to identify which interactions might be significant before conducting the experiment, through their knowledge of the subject matter." (Yang and El-Haik, 2009)*

Using Taguchi design for finding optimal hyperparameter of a genetic algorithm has been successfully performed by Dao, Abhary, and Marian, 2016 as well as Naruka et al., 2019.

Taguchi predefined a number of different orthogonal arrays where each row contains the specific levels (i.e the settings) of one experiment, while the columns correspond the factors (Hamzaçebi, 2021). Taguchi's orthogonal arrays "represent the smallest fractional factorials" (Roy, 1990). Only a fraction of combinations needs to be tested, drastically reducing computational needs.

The researcher has the responsibility to select an array based on the individual needs (Hamzaçebi, 2021). Using these orthogonal arrays instead of full factorial experiments will lead to a much smaller amount of simulation runs, while the full factorial experiments "might not provide appreciably more useful information" (Roy, 1990).

A big drawback of using Taguchi orthogonal arrays is the inability of evaluating higher order interaction effects. It is only possible to measure the interaction between 2-level factors. Not only are higher order interaction effects not possible to evaluate, they also have an influence on the performance. Orthogonal array experiments perform best in cases of minimal

## 4 Hyperparameter Tuning

---

interaction between factors. While there is still a good chance of identifying the optimum condition, especially the performance estimate can be significantly off (Roy, 1990).

While Yang and El-Haik, 2009 state that in many cases higher-order interaction effects in factorial designs are seldom significant, this might not be the case for genetic algorithms. For example K. De Jong, 2007 claimed, that control parameters of a genetic algorithm “interact in highly non-linear ways.” If the proposed method is able to provide a suitable set of hyperparameter settings will be evaluated chapter 5.

ref both ga taguchi paper and say, that in no cases interactions were analysed

**Selection of an Orthogonal Array** When choosing a suitable Taguchi orthogonal array, various factors have to be taken into account. According to Yang and El-Haik, 2009, a three step procedure needs to be followed:

1. Calculate the total degree of freedom (DOF).
2. Based on the following two rules a standard orthogonal array should be selected:
  - a) Total DOF need to be smaller than the number of runs provided by the orthogonal array.
  - b) All required factor level combinations need to be accommodated by the orthogonal array.
3. Factors have to be assigned using these rules:
  - a) In case the factor level does not fit into the orthogonal array, methods such as column merging and dummy level can be used to modify the original array.
  - b) Using the linear graph and interaction table, interactions can be defined.
  - c) In case some columns are not assigned, its possible to keep these columns empty.

For this design of experiment, 7 factors (3 factors of level 4 and 4 factors of level 2) have been selected. Which factors and levels to choose was done based on experience gained on section 4.2. In table 4.3.1, every factor with the corresponding levels has been listed.

### 4.3 Design of Experiment

---

Factors	Code	Level 1	Level 2	Level 3	Level 4
CrossoverType	A	one point	two point	uni* 0.1	uni* 0.5
CrossoverRate	B	0.2	0.5	0.8	0.9
MutationRate	C	0.01	0.1	0.3	0.5
ChromosomeType	D	Time	Time+NPC	-	-
GeneType	E	Int	Dict	-	-
TournamentSize	F	2	4	-	-
IndMutationRate	G	0.1	0.5	-	-

Table 4.3: Control Parameters (Factors) with corresponding Settings (Levels) - (\*uniform)

It is important to state, that Taguchi allows to only test for possible (pre determined) two-factor interactions, evaluating higher factor interactions is not possible (Yang and El-Haik, 2009). Analysing interactions comes at the cost of degrees of freedom. An interaction between ChromosomeType and GeneType might be of interest and will thus be chosen. In order to minimized the required degrees of freedom (and correspondingly the required number of experiment runs), no additional interactions will be analysed.

#### 4.3.2 Selection of a Suitable Standard Orthogonal Array

The total degree of freedom can be calculated using the rules provided by Yang and El-Haik, 2009:

1. 1 DOF is always used for the overall mean.
2. Each factor has a DOF of NumberOfLevels - 1.
3. Two-factor interactions use this equation to calculate DOF:  $(n_{factor1} - 1)(n_{factor2} - 1)$  where  $n$  = number of levels.

This leads to the following calculation for the needed 3 factors of level 4 and 4 factors of level 2 as well as the interaction ChromosomeType-GeneType:

$$DOF = 1 + 3 * (4 - 1) + 4 * (2 - 1) + 1 * (2 - 1) * (2 - 1) = 15 \quad (4.1)$$

## 4 Hyperparameter Tuning

---

A  $L_{16}$  array seems suitable to accommodate the required 15 DOF, which can be seen in table 4.3.2.

NO.	$L_{16}(2^{15})$														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2
3	1	1	1	2	2	2	2	1	1	1	1	2	2	2	2
4	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1
5	1	2	1	1	1	2	2	1	1	2	2	1	1	2	2
6	1	2	2	1	1	2	2	2	2	1	1	2	2	1	1
7	1	2	2	2	2	1	1	1	1	2	2	2	2	1	1
8	1	2	2	2	2	1	1	2	2	1	1	1	1	2	2
9	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
10	2	1	2	1	2	1	2	2	1	2	1	2	1	2	1
11	2	1	2	2	1	2	1	1	2	1	2	2	1	2	1
12	2	1	2	2	1	2	1	2	1	2	1	1	2	1	2
13	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1
14	2	2	1	1	2	2	1	2	1	1	2	2	1	1	2
15	2	2	1	2	1	1	2	1	2	2	1	2	1	1	2
16	2	2	1	2	1	1	2	2	1	1	2	1	2	2	1

Table 4.4:  $L_{16}(2^{15})$  Taguchi orthogonal array taken from Roy, 1990

4 level factors need additional space which will be generated using column merging, while the interaction will need to be assigned as well. Either an interaction table or linear graphs of the  $L_{16}$  array can be used for both column merging and interaction assignment (NazanDanacioglu, 2005). Both illustrate the interaction relationships in the orthogonal array (Yang and El-Haik, 2009). The linear graph is more straight forward and will be the chosen approach. While there are multiple linear graphs for the  $L_{16}$  array, 4.3.2 describes the graph which best fits the requirements from table 4.3.1. If no suitable graph is found, they can be modified using rules described by NazanDanacioglu, 2005.

### 4.3 Design of Experiment

---

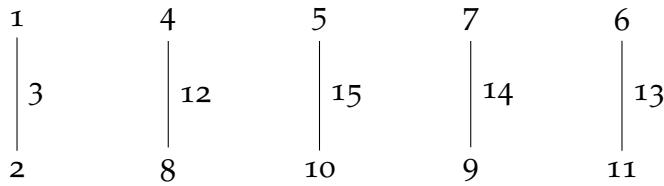


Figure 4.2: Linear Graph of  $L_{16}(2^{15})$  taken from Yang and El-Haik, 2009

In a Taguchi linear graph, the nodes as well as the connections both represent columns in the orthogonal array. The interaction between two nodes is described by the connecting line (Taguchi et al., 2005). This is useful for both analysing interactions between columns as well as combining (merging) interacting columns in case a higher factor is needed.

**Column Merging** A, B and C are both 4 level factors. The currently selected orthogonal array only fits 2 level factors. Column merging, it is possible to extend columns to accommodate higher order levels.

As calculated in 4.1, a four-level column requires three degrees of freedom, thus three two-level columns need to be merged. Column merging needs the to be merged columns to be part of an interaction group (Yang and El-Haik, 2009). The available interaction groups are visualized by the linear graph in figure 4.3.2.

3 2-level interaction columns need to be selected first. One column is discarded, the remain two columns are merged using the rules in tabular 4.5.

OLD COLUMN		NEW COLUMN
1	1	->
1	2	->
2	1	->
2	2	->

Table 4.5: Rules taken from Roy, 1990

## 4 Hyperparameter Tuning

---

The four-level factor can then be assigned to this newly generated column. Because three four-level factors are needed for the current experiment, nine two-level columns have to be merged in total.

**Assigning Interactions** The interaction between both two-level factors can be assigned using the linear graph as well. An interaction between ChromosomeType and GeneType seems possible, thus D and E will be assigned to connected nodes in the linear graph. The resulting graph can be seen in 4.3.2. An interaction between F and G can not be investigated, as the chosen orthogonal array is not able to fit the additional 1 degree of freedom (see equation 4.1).

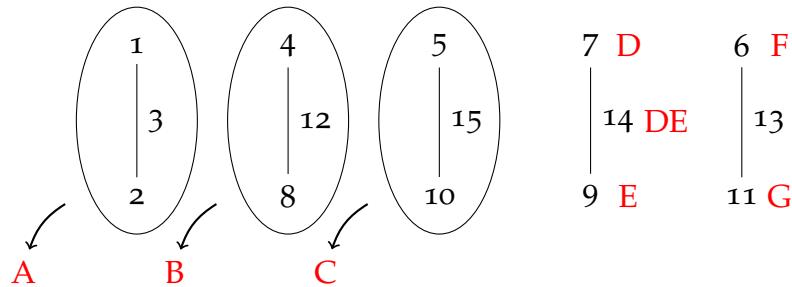


Figure 4.3: Modified Linear Graph to fit our needs

Combining columns 1 2 3 to A, 4 8 12 to B and 5 10 15 to C using rules defined by table 4.5 is done in 4.6.

Removing the old and inserting the new columns in the table and transcoding 7 to D, 9 to E, 14 to DE, 6 to F, 11 to G and 13 to FG results in the final table 4.7. This combination table will subsequently be used as settings for the simulation runs.

### 4.3.3 Result Analysis

The final table 4.7 will be used for running all the needed testcases (the interaction columns can be ignored until the evaluation). Transcoding all

### 4.3 Design of Experiment

---

NO.	1	2	3	4	8	12	5	10	15
1	1-1 > 1			1-1 > 1			1-1 > 1		
2	1-1 > 1			1-2 > 2			1-2 > 2		
3	1-1 > 1			2-1 > 3			2-1 > 3		
4	1-1 > 1			2-2 > 4			2-2 > 4		
5	1-2 > 2			1-1 > 1			1-2 > 2		
6	1-2 > 2			1-2 > 2			1-1 > 1		
7	1-2 > 2			2-1 > 3			2-2 > 4		
8	1-2 > 2			2-2 > 4			2-1 > 3		
9	2-1 > 3			1-1 > 1			2-1 > 3		
10	2-1 > 3			1-2 > 2			2-2 > 4		
11	2-1 > 3			2-1 > 3			1-1 > 1		
12	2-2 > 3			2-2 > 4			1-2 > 2		
13	2-2 > 4			1-1 > 1			2-2 > 4		
14	2-2 > 4			1-2 > 2			2-1 > 3		
15	2-2 > 4			2-1 > 3			1-2 > 2		
16	2-2 > 4			2-2 > 4			1-1 > 1		

Table 4.6: Building 4 Level columns from 2 Level columns

factors and levels to get the corresponding setting can be done using the table from 4.3.1. Every setting will be repeated 8 times to reduce randomness and gain information about variance. Running the genetic algorithm with these 16 different settings each repeated 8 times took 10 days on the two in section 4.1 described workstations. The results are found in the appendix at 1.

## ANOVA

ANOVA analysis (analysis of variance) will provide information on the magnitude of contribution of the main effects and interactions. The calculation of ANOVA on a Taguchi experiment is the same as for a classical design of experiment (Yang and El-Haik, 2009). Calculating ANOVA is done using the programming language R<sup>3</sup> and the result can be seen in table 4.8.

<sup>3</sup><https://www.r-project.org/>

## 4 Hyperparameter Tuning

---

NO.	A	B	C	D	E	F	G	DE
1	1	1	1	1	1	1	1	1
2	1	2	2	1	2	1	2	2
3	1	3	3	2	1	2	1	2
4	1	4	4	2	2	2	2	1
5	2	1	2	2	1	2	2	2
6	2	2	1	2	2	2	1	1
7	2	3	4	1	1	1	2	1
8	2	4	3	1	2	1	1	2
9	3	1	3	2	2	1	2	1
10	3	2	4	2	1	1	1	2
11	3	3	1	1	2	2	2	2
12	3	4	2	1	1	2	1	1
13	4	1	4	1	2	2	1	2
14	4	2	3	1	1	2	2	1
15	4	3	2	2	2	1	1	1
16	4	4	1	2	1	1	2	2

Table 4.7: Final version of used Taguchi orthogonal array

The sum of squares of a model tell how much of the total variation is explained by the model. The variance is broken down into the factors A-G along with the interaction D:E. The residual sum of squares shows the difference between the models prediction versus what was actually observed (i.e the variance that can not be explained by the model) (A. P. Field, Miles, and Z. Field, 2012).

The F ratio (or value) measures the ratio of variance explained by the factor and the variation explained by the error term (A. P. Field, Miles, and Z. Field, 2012). Simply speaking, how good is the model versus how bad is the model.

Finally, the p value (in column labelled Pr(>F)) shows how likely the size of the given F ratio is obtained in case there is no effect on the results. Commonly, if p is smaller than 0.05, the effect can be viewed as statistically significant (A. P. Field, Miles, and Z. Field, 2012).

The higher number of DOF can be explained with the number of repetitions

### 4.3 Design of Experiment

---

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
A	3	23.89	7.96	6.59	0.0004
B	3	5.00	1.67	1.38	0.2532
C	3	34.32	11.44	9.46	0.0000
D	1	3.88	3.88	3.21	0.0759
E	1	0.35	0.35	0.29	0.5912
F	1	18.91	18.91	15.64	0.0001
G	1	6.98	6.98	5.77	0.0179
D:E	1	4.10	4.10	3.40	0.0680
Residuals	113	136.60	1.21		

Table 4.8: ANOVA results

and can be calculated with the equation 4.2 (taken from Roy, 1990).

$$\begin{aligned}
 DOF &= \text{totalNumberOfResults} - 1 \\
 &= \text{numberOfTrials} * \text{numberOfRepetitions} - 1 \quad (4.2) \\
 &= 16 * 8 - 1 = 127
 \end{aligned}$$

The multiple R-squared value of the model is 0.416 while the adjusted R-squared value is 0.344. Multiple R-squared gives a measure on how much variability in the outcome is explained by the predictors (A. P. Field, Miles, and Z. Field, 2012). Having only 41.6% does not seem optimal. A. P. Field, Miles, and Z. Field, 2012 state further that a model which generalizes well has an adjusted R-squared value that is similar to multiple R-squared, which is also not the case in this scenario. The high error might possibly be explained by the huge search space in the scenario. Increasing the population and number of generations might lead to improvements, however at the cost of computational time. If the model, having this much of an error, will perform well compared to either a genetic algorithm build from values from the literature or compared to random search will be evaluated in section 5.

Looking at the factors as well as the interaction, significant main effects can be seen. The highest F value has the main effect F (TournamentSize). The

## 4 Hyperparameter Tuning

---

effect is significant with  $F(1, 112) = 15.64, p < 0.001$ . Next, the effect C (MutationRate) is significant with  $F(3, 112) = 9.46, p < 0.001$ . A (CrossoverType) is also significant  $F(3, 112) = 6.59, p < 0.001$ . Finally G (IndependentMutationRate) is significant with  $F(1, 112) = 5.77, p < 0.05$ . D (ChromosomeType) and the interaction D:E will be mentioned as well with  $F(1, 112) = 3.21, p < 0.1$  and  $F(1, 112) = 3.4, p < 0.1$  respectively. There is not enough evidence that suggests significant main effects for the factors B (CrossoverRate) and E (GeneType).

Especially the fact, that the CrossoverRate does not show significant effects is surprising, which is not supported by the literature (todo: find references). The low influence of GeneType however might be explained by the fact, that it does not have a huge impact on the action selected apart from more granularity of the parameters when Dictionary encoding is used.

To look at the percentage contribution of each factor the formulas 4.3 and 4.4 (gathered by Yang and El-Haik, 2009) are used.

$$SS_T = SS_A + SS_B + SS_C + \dots + SS_{error} \quad (4.3)$$

Example calculation for factor A.

$$contribution_A = SS_A / SS_T * 100 \quad (4.4)$$

The percentage contribution of all factors is plotted in 4.3.3 and shows the high error of the model.

### Main-effects and interaction chart

Identifying the optimal conditions needs analysis of the main effects per factor. They allow to predict the levels, that lead to the best result (Roy, 1990).

*“The main-effects chart is a plot of average responses at different levels of a factor versus the factor levels.” (Yang and El-Haik, 2009)*

### 4.3 Design of Experiment

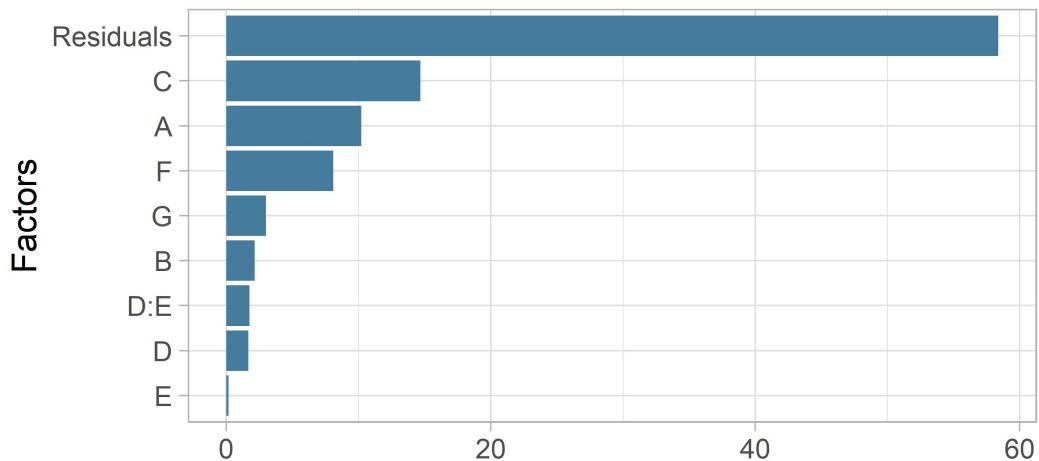


Figure 4.4: Percentage Contribution

For every factor, sum up the mean of all results per level, then divide by the number of runs per level.

The resulting main-effect charts can be seen in figure 4.3.3.

Show calculation example for D

In case there is no interaction, the optimal setting is easily determined by using the main effects chart. Go over every factor in the chart and use the best level (in case of this experiment, the level with the highest value).

If interactions exist, they might have an influence on the best settings and need further investigation (Yang and El-Haik, 2009). To investigate the previously defined interaction an interaction graph can be used. The calculation is similar to calculating main effects and shown in figure 4.3.3.

Show calculation example for DE

The crossing of lines indicates, that an interaction between the two factors might exist (A. P. Field, Miles, and Z. Field, 2012). The more parallel the lines are, the less likely an interaction. Magnitude of the angle between the lines corresponds to the degree of interaction presence, according to (Roy, 1990).

## 4 Hyperparameter Tuning

---

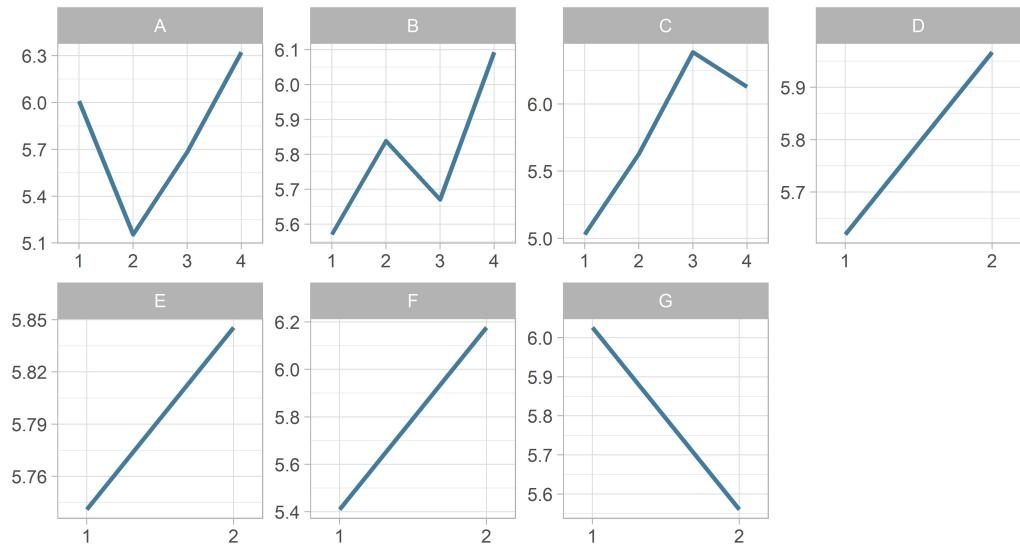


Figure 4.5: Main Effects

### Selection of optimal setting

When choosing the optimal setting, the first step is to look at the best main effects combination. For this experiment, the best combination according to the main effects is the following: A<sub>4</sub>, B<sub>4</sub>, C<sub>3</sub>, D<sub>2</sub>, E<sub>2</sub>, F<sub>2</sub>, G<sub>1</sub>.

Analysing the ANOVA table, the interaction D:E however seems to have significance, especially compared to E. According to (A. P. Field, Miles, and Z. Field, 2012), it makes little sense to further interpret main effects if the interaction effect is significant (which it almost is with  $p < 0.1$ ), thus this interaction will be integrated.

The test of interaction in figure 4.3.3 suggest D<sub>2</sub> and E<sub>1</sub> as the best combination. This is optimal, as D<sub>2</sub> is also recommended by the main effects. While E<sub>1</sub> does not correspond to its main effect, the low F value suggests low significance for E anyway. Concluding this line of thought, the combination A<sub>4</sub>, B<sub>4</sub>, C<sub>3</sub>, D<sub>2</sub>, E<sub>1</sub>, F<sub>2</sub>, G<sub>1</sub> seems to be optimal.

### 4.3 Design of Experiment

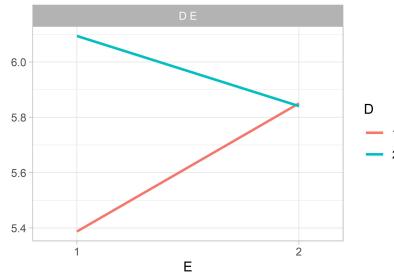


Figure 4.6: Test of interactions

**Optimum performance calculation** To calculate the predicted results of an algorithm with these settings, optimal performance calculation can be used. Equation 4.5 only uses the optimal main effects while equation 4.6 has the interaction D:E applied. The calculation formulas are provided by Roy, 1990.

$$\begin{aligned}
 Y_{opt} &= \bar{T} + (\bar{A}_4 - \bar{T}) + (\bar{B}_4 - \bar{T}) + (\bar{C}_3 - \bar{T}) + (\bar{D}_2 - \bar{T}) + \\
 &\quad (\bar{E}_2 - \bar{T}) + (\bar{F}_2 - \bar{T}) + (\bar{G}_1 - \bar{T}) \\
 &= 8.06
 \end{aligned} \tag{4.5}$$

$$\begin{aligned}
 Y_{opt} &= \bar{T} + (\bar{A}_4 - \bar{T}) + (\bar{B}_4 - \bar{T}) + (\bar{C}_3 - \bar{T}) + (\bar{D}_2 - \bar{T}) + \\
 &\quad (\bar{E}_1 - \bar{T}) + ([\bar{D}x\bar{E}]_2 - \bar{T}) + (\bar{F}_2 - \bar{T}) + (\bar{G}_1 - \bar{T}) \\
 &= 8.13
 \end{aligned} \tag{4.6}$$

Utilizing the interaction D:E, the performance estimation improves from 8.06 to 8.13. Finally the optimized settings are as follows: CrossoverType: Uniform 0.5, CrossoverProbability: 0.9, MutationProbability: 0.3, ChromosomeType: Time+NPC, GeneType: Integer, TournamentSize: 4 and IndividualMutationProbability: 0.1.

Talk about high randomness in the recommended settings

### **signal-to-noise (S/N)**

As previously discussed, the ANOVA model has a high error, which suggests high randomness. Taguchi recommends using signal-to-noise (S/N) ratio to reduce the variability, as using only the mean of the results does not take the variation into account (Roy, 1990). The greater the signal-to-noise ratio, the smaller the variance.

*“use of the S/N ratio offers an objective way to look at the two characteristics (consistency and average value) together.” (Roy, 1990)*

S/N is calculated in two steps, according to Roy, 1990. First the mean square deviation (MSD) is needed. Depending on the quality characteristic, a different equation has to be chosen. In this case, a higher result is better, thus equation 4.7 is used for each repetition, with  $y$  being a result and  $n$  the number of repetitions.

$$MSD = (1/y_1^2 + 1/y_2^2 + 1/y_3^2 + \dots)/n \quad (4.7)$$

S/N is further calculated using equation 4.8.

$$S/N = -10\log_{10}(MSD) \quad (4.8)$$

Generating main effects and ANOVA is now done using S/N instead. As a side note, only 15 DOF for the ANOVA analysis are available, as repetitions per run get merged into 1 result (in contrast to 4.1), which can be seen in equation 4.9.

$$\begin{aligned} DOF &= totalNumberOfResults - 1 \\ &= numberOfRowsTrials * 1 - 1 \\ &= 16 - 1 = 15 \end{aligned} \quad (4.9)$$

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
A	3	5.14	1.71	3.54	0.3682
B	3	2.04	0.68	1.40	0.5397
C	3	10.59	3.53	7.28	0.2644
D	1	1.29	1.29	2.67	0.3498
E	1	0.39	0.39	0.81	0.5329
F	1	4.43	4.43	9.15	0.2033
G	1	2.28	2.28	4.70	0.2751
D:E	1	0.92	0.92	1.89	0.4005
Residuals	1	0.48	0.48		

Table 4.9: S/N ANOVA results

The resulting ANOVA table can be seen in 4.9.

When looking at the p values of this table, it is obvious that no factor can discard the null-hypothesis, which states that a factor has no significant effect. Considering this fact, it was deemed to not be necessary to perform further investigations. The often recommend Signal to Noise ratio does not seem to suitable for this experiment, thus the previously calculated settings in paragraph 4.3.3 will not be adjusted.

### Elite Selection

Although the optimal hyperparameter setting are discussed in chapter 5, a problem was obvious when analysing results of a GA using the settings from 4.3.3. Setbacks in the optimal cost between two generations happen frequently, likely due to the high crossover and mutation rates. In order to mitigate this problem, it was decided to implement elite selection with a size of 2. Per generation, the two best individuals are now copied into the next generation without modifications, which makes worse performance between generations not possible. It is important to note, that the two best individuals can still be selected by tournament selection for modification, its just that a copy of them is saved. Figure 4.3.3 compares both no elite selection with an elite selection of 2. For a few selected repetitions, the best individual cost per generation is plotted.

## 4 Hyperparameter Tuning

---

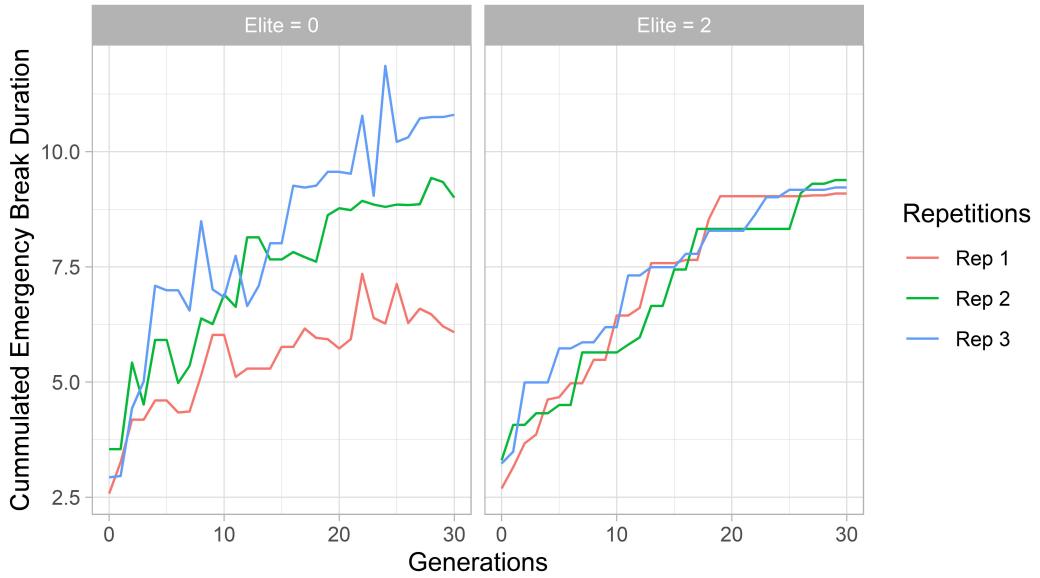


Figure 4.7: Elite Selection Comparison

For analysing the statistical significance in the differences in mean between the a genetic algorithm using elite selection of 2 vs no elite selection, a t-test can be used. In order to ignore possible violation of the assumption of homogeneity, a robust welch t-test is applied which adjusts the DOF accordingly (A. P. Field, Miles, and Z. Field, 2012).

On average, using elite improved the performance ( $M = 8.52$ ,  $SE = 0.31$ ), compared to using no elite ( $M = 7.92$ ,  $SE = 0.55$ ). This difference was not significant  $t(14.21) = 0.96$ ,  $p > 0.05$ ; however, it did represent a small-sized effect  $r = 0.25$ . A comparison of both settings each repeated 10 times can be seen in figure 4.3.3.

Due to the existence of the mentioned small effect, it is concluded that the slightly modified version of the settings from 4.3.3 will be used in chapter 5, where elite selection is set to 2.

**Effect Size** According to A. P. Field, Miles, and Z. Field, 2012 effect sizes provide an objective measure on the importance of an effect, where 0 means

### 4.3 Design of Experiment

---

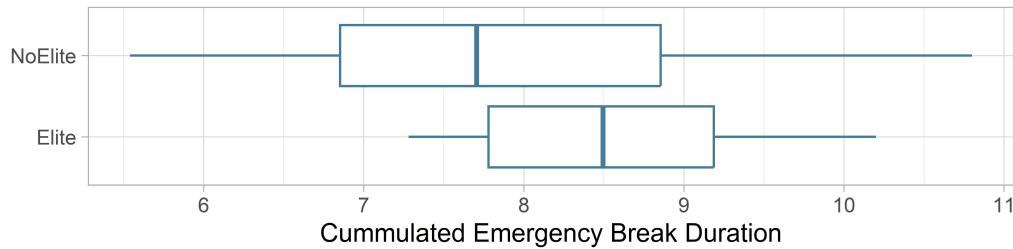


Figure 4.8: Comparison Elite Selection vs No Elite Selection

no effect and 1 means a perfect effect. They allow for a standardized measure and are not affected by sample size. He further recommends to use the widely used suggestions made by Cohen (Cohen, 1988, Cohen, 1992) on defining between a large or small effect:

- $r = .10$  (small effect): The effect explains 1% of the variance.
- $r = .30$  (medium effect): The effect explains 9% of the variance.
- $r = .50$  (large effect): The effect explains 25% of the variance.

Effect sizes will be further used to compare different algorithms in chapter 5 as well and are calculated for a t test using equation 4.10.

$$r = \sqrt{\frac{t^2}{t^2 + DOF}} \quad (4.10)$$



# 5 Evaluation

This chapter will compare the GA settings proposed in 4.3.3 with the best settings found in 4.2 as well as with random search. The three different algorithms that are going to be compared are as follows:

- **Default Genetic Algorithm** - using the best settings found in 4.2
  - CrossoverType: Two-Point, CrossoverRate: 0.8, MutationRate: 0.20, TournamentSize: 4, ChromosomeType: Time, GeneType: Integer, IndividualMutationRate: 0.1 and EliteSelection: 0.
  - The algorithm will be run 10 times. The population of 96 needs to be simulated 31 times per run (30 generations + initialization), which leads to  $96 * 31 * 10 = 29,760$  simulations.
- **Optimized Genetic Algorithm** - using the recommended settings found in 4.3.3
  - CrossoverType: Uniform 0.5, CrossoverRate: 0.9, MutationRate: 0.3, ChromosomeType: Time+NPC, GeneType: Integer, TournamentSize: 4 and IndividualMutationRate: 0.1 and EliteSelection: 2.
  - The algorithm will be run 10 times. The population of 96 needs to be simulated 31 times per run (30 generations + initialization), which leads to  $96 * 31 * 10 = 29,760$  simulations.
- **Random Search**
  - Randomly choosing actions, using the probabilities from table 3.1.
  - The algorithm will be run 10 times each with 2,976 simulations, always taking the maximum value as the result. 29,760 simulations were executed in total.

## 5 Evaluation

---

The evaluation is done over 4 different start scenarios which can be found at the appendix 6.2.2.

### 5.1 Start Scenario 1

First, a comparison of the three algorithms on start scenario 1 was made. This is the same start scenario, that was used in chapter 4. The results are shown in figure 5.1.

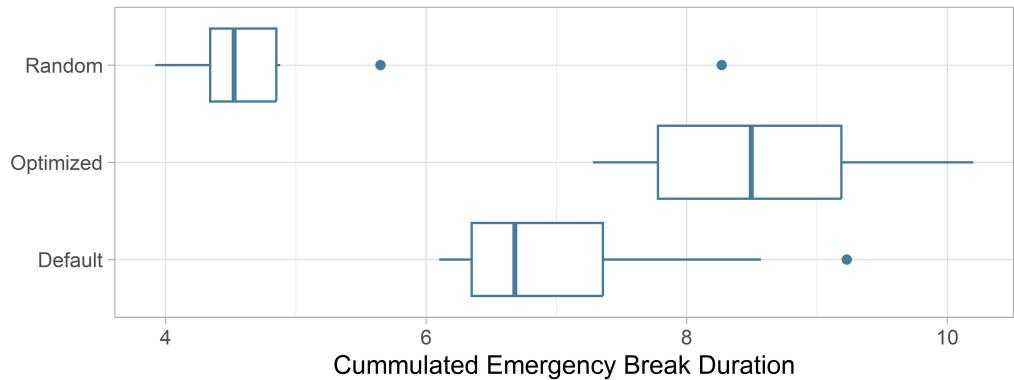


Figure 5.1: Start Scenario 1: Default GA vs Optimized GA vs Random Search

Analysing the graph, the Optimized GA clearly outperformed the Default GA as well as Random Search.

Welchs t-test shows that on average, greater fitness is achieved by using Optimized GA ( $M = 8.52$ ,  $SE = 0.31$ ) than from using Default GA ( $M = 7.09$ ,  $SE = 0.34$ ). This difference was significant  $t(17.87) = 3.15$ ,  $p < .01$ . It did represent a large effect  $r = 0.60$ . Compared to Random ( $M = 4.943$ ,  $SE = 0.4$ ), the Optimized GA has even higher dominance, with a significant difference  $t(16.9) = 7.12$ ,  $p < .001$  and a large effect  $r = 0.87$ .

The better performance of the Optimized GA was however unsurprising, as it was specifically trained on the used start scenario.

To further analyse both genetic algorithms, a look at their performance over the generations next to their diversity chart is of interest. Figure 5.1 plots the mean over 10 repetitions, the outline show the first and third quantiles.

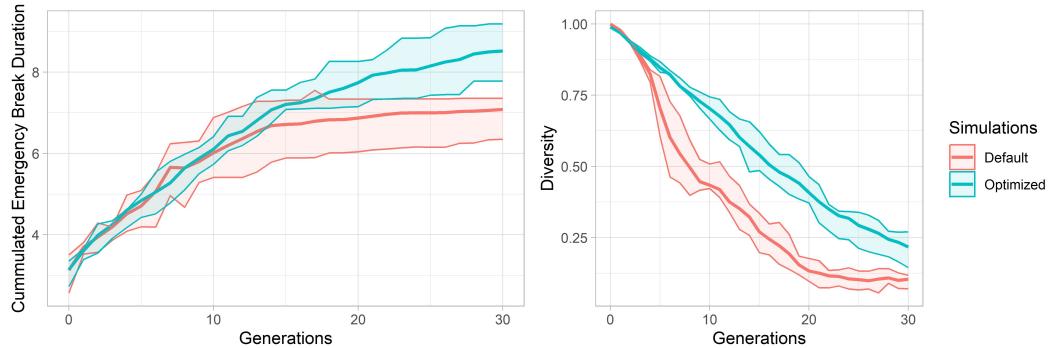


Figure 5.2: Start Scenario 1: Comparison of GAs

After generation 10, the rate of improved fitness of the Default GA drops compared to the Optimized GA. A combined early sharp decline in the diversity, suggests a connection. The Optimized GA shows to hold the diversity in the population longer, its rate of convergence is linear. Its high crossover and mutation rates seem to help with the improved diversity. The graph also shows, that a higher number of generations might not be useful for improved performance, as after 30 generations, the Optimized GA does not seem to hold enough diversity to continue with adequate performance gains.

## 5.2 Start Scenario 2

Start scenario 2 has with 9 vehicles and 5 pedestrians the same amount of NPCs as start scenario 1 and is described in more detail in Appendix 1.

Figure 5.2 shows, that the Optimized GA can also provide better results compared to the other two algorithms in start scenarios where it has not been trained on. The Optimized GA ( $M = 9.24$ ,  $SE = 0.3$ ) achieves better fitness on average compared to the Default GA ( $M = 7.46$ ,  $SE = 0.31$ , with a significant difference  $t(17.98) = 4.19$ ,  $p < 0.001$  and a large effect of  $r = 0.7$ ). The difference

## 5 Evaluation

---

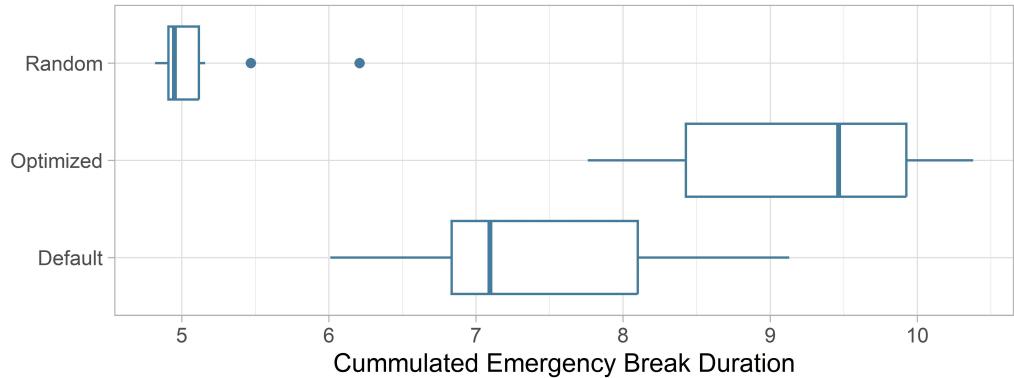


Figure 5.3: Start Scenario 2: Default GA vs Optimized GA vs Random Search

in the average fitness value compared Random Search ( $M = 5.13$ ,  $SE = 0.13$ ) is significant as well with  $t(12.57) = 12.7$ ,  $p < 0.001$  and a large effect of  $r = 0.96$ .

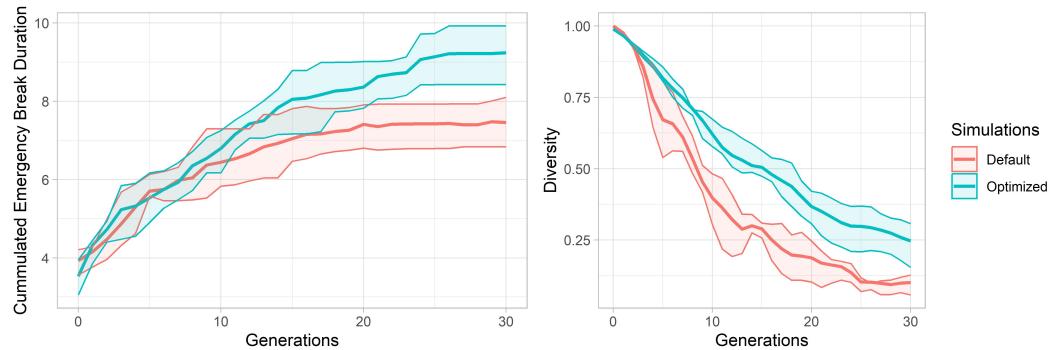


Figure 5.4: Start Scenario 2: Comparison of GAs

The comparison shown in figure 5.2 seams very similar to the comparison discussed in start scenario 1. On the one hand, the Default GA shows a slower performance increase starting already from generation 8. On the other hand, the diversity of the Optimized GA drops a bit sooner. Still both evaluations show, that the Optimized GA performs well in start scenarios with the given amount of NPCs.

## 5.3 Start Scenario 3

Start scenario 3 is described in more detail in Appendix 2. 5 vehicles with 3 pedestrians are initialized, resulting in a simulation with only a small number of NPCs.

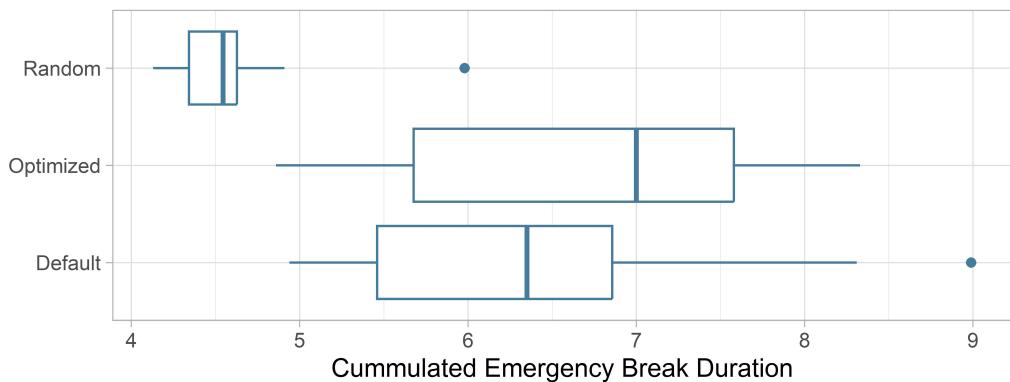


Figure 5.5: Start Scenario 3: Default GA vs Optimized GA vs Random Search

Looking at the graph, the Optimized GA again outperforms the Random Search, however there seems to be only marginal improvements compared to Default GA.

A t-test confirms these findings. While on average, greater fitness is achieved by using Optimized GA ( $M = 6.66$ ,  $SE = 0.38$ ) than from using Default GA ( $M = 6.49$ ,  $SE = 0.42$ ). This difference was however not significant  $t(17.83) = 0.29$ ,  $p > .05$  and an effect size of  $r = 0.07$ . Verifying the better performance of the Optimized GA compared to Random Search ( $M = 4.619$ ,  $SE = 0.17$ ) shows a significant difference  $t(12.4) = 4.9$ ,  $p < .001$  and a large effect size of  $r = 0.81$ .

To further analyse both genetic algorithms, their performance over the generations next to their diversity chart is again shown in figure 5.3. The mean over 10 repetitions is plotted, the outline show the first and third quantiles.

The rate of improved fitness of the Default GA now drops very similar to the Optimized GA. The early decline in the diversity is also not as pronounced

## 5 Evaluation

---

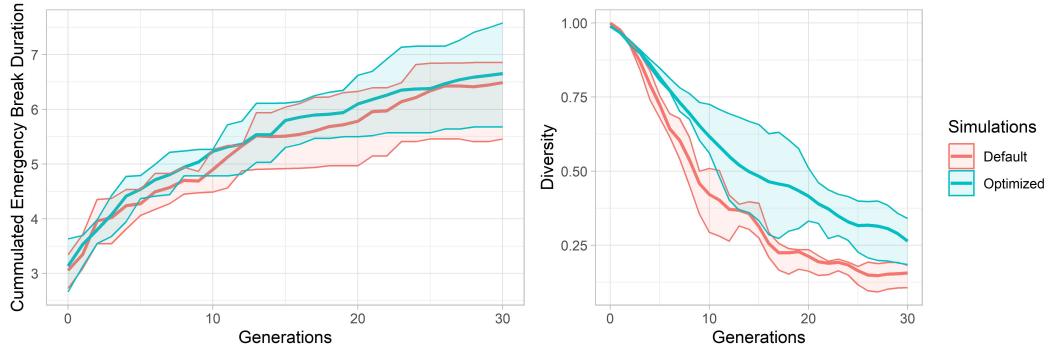


Figure 5.6: Start Scenario 3: Comparison of GAs

as in the previous comparisons. While the optimized GA shows to still hold the diversity in the population longer, this only has a minimal impact on its average fitness. The similarity in performance might be explained by the smaller search space due to the smaller number of NPCs. Here, high mutation and crossover rates might not have the previous pronounced advantage.

## 5.4 Start Scenario 4

Start scenario 4 can be seen in Appendix at 2. 18 vehicles with 10 pedestrians are initialized, resulting in the simulation with the most NPCs.

Figure 5.4 shows the Optimized GA clearly outperforming the Default GA as well as Random Search. The Optimized GA ( $M = 10.60$ ,  $SE = 0.29$ ) has significantly greater fitness than the Default GA ( $M = 8.46$ ,  $SE = 0.28$ ) with  $t(17.98) = 5.30$ ,  $p < .001$  and a large effect  $r = 0.78$ . Compared to Random Search ( $M = 6.86$ ,  $SE = 0.14$ ), the greater fitness of the Optimized GAs is significant with  $t(11.71) = 12.7$ ,  $p < .001$  and a large effect  $r = 0.96$ .

Both genetic algorithms performance over the generations next to their diversity chart is compared in figure 5.4.

Already at generation 5, the average rate of improved fitness of the Default GA drops compared to the Optimized GA. This is accompanied by an early

#### 5.4 Start Scenario 4

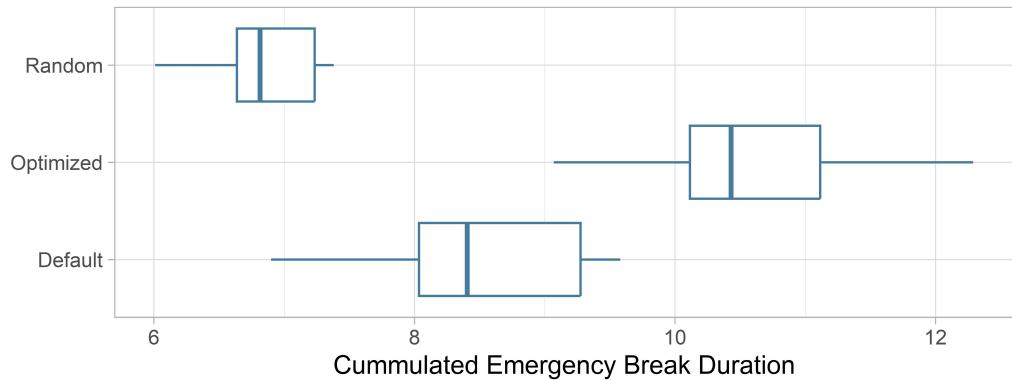


Figure 5.7: Start Scenario 4: Default GA vs Optimized GA vs Random Search

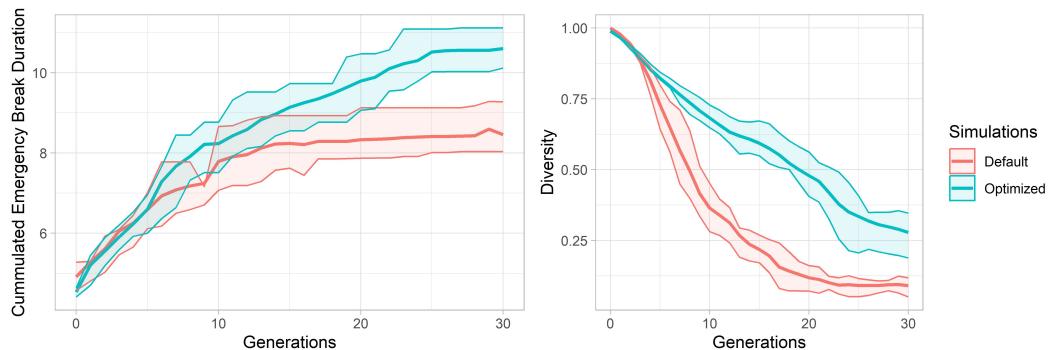


Figure 5.8: Start Scenario 4: Comparison of GAs

sharp decline in the diversity. The optimized GA again shows be able to hold the diversity much longer at a high level, its rate of diversity drop is linear. The results underline the statement made in section 5.3, which claims, that the Optimized GA excels at scenarios with lots of NPCs, where a vast search space is given.



# 6 Conclusion

This masters thesis first explained both the concept of genetic algorithms as well as behavior trees in chapter 2. In the subsequent chapter, the design and implementation of both tools is outlined. The stated search goal lies in the domain of autonomous vehicle testing, specifically in finding critical scenarios. In order to find such results, the behavior tree aims to control the EGO vehicle in a realistic manner while the genetic algorithm maximises its cumulated emergency stop duration by commanding all NPCs in the scenario. In chapter 4, this masters thesis successfully optimized control parameters of a genetic algorithm using first literature research accompanied by comparison testing in order to find a suitable population size. Utilizing a taguchi orthogonal array, the remaining hyperparameter were selected and evaluated for their significance. Finally, the genetic algorithm using the optimized parameters is evaluated in chapter 5. The evaluated genetic algorithm displays good performance on the given search problem. The results show, that the optimized settings for a GA provide significant improvements in most start scenarios compared to general settings from the existing literature as well as compared to random search. Only in the case of a small number of NPCs, the performance seems to be on par with a genetic algorithm utilizing settings from the literature.

## 6.1 Research Questions

### 6.1.1 Research Question 1

*Is a genetic algorithm suitable for generating critical driving scenarios compared to random search?*

Compared to random search, research question 1 definitely holds true. The optimized genetic algorithm will drastically improve performance when using the given cost function. In all four analysed starting scenarios, random search resulted overall in significantly worse results. There were no cases where a random search run surpassed the mean result of the optimized genetic algorithm runs.

### 6.1.2 Research Question 2

*Is it possible to improve the performance of a genetic algorithm by optimizing the control parameter using the taguchi method?*

The second research question can be answered as well with yes. The genetic algorithm that was optimized utilizing the taguchi method showed pronounced improvements in 3 of the 4 start scenarios compared to using control parameters suggested by the literature. Only in one start scenario with a small number of NPCs, the difference was not significant. It can be concluded, that taguchi orthogonal testing, which only needs a minimal amount of experiment runs, can lead to impressive performance improvements when it comes to optimizing the control parameter of a genetic algorithm.

## 6.2 Outlook and Future Work

Significant improvements to the genetic algorithm as well as to the Traffic Manger are possible. Two main paths seem to provide valuable enhancements.

### 6.2.1 Additional Actions

Although the provided actions by the Action Interface (see section 3.1.1) already produce a vast search space, additional actions might improve variation in the results and provide even more complex critical scenarios.

Examples for new actions are applying a lane offset, ignoring red traffic lights or simulating a blown tire.

Implementing these actions will in some cases require only minimal effort and will allow a genetic algorithm to use even more complex action sequences for its search.

### 6.2.2 Oracles

Utilizing oracle functions in order to select interesting scenarios during the runtime of a genetic algorithm was already done by Almanee et al., 2021. Multiple oracle functions will test for different thresholds. For example, one oracle function might check, if the ego vehicle has exceeded the speed limit, a different function checks for crashes where the ego vehicle is at fault. Other ideas include having an oracle which evaluates if the comfort level of the passenger is under a certain threshold.

These functions will test each individual in the population. In case one or multiple functions return true, the individual scenario will be saved and automatically categorized according to the types of thresholds. The genetic algorithm however remains unaffected.

Oracles have the potential to extract multiple different scenarios from only one genetic algorithm run. The automatic categorization drastically improves the usefulness of this testing approach. Otherwise each search result needs to be evaluated manually for finding errors in the autonomous driving system.



# Bibliography

- Almanee, Sumaya et al. (2021). "scenoRITA: Generating Less-Redundant, Safety-Critical and Motion Sickness-Inducing Scenarios for Autonomous Vehicles." In: Publisher: arXiv Version Number: 1. DOI: 10.48550/ARXIV.2112.09725. URL: <https://arxiv.org/abs/2112.09725> (visited on 10/19/2023) (cit. on pp. 2, 27, 59).
- Ayoub, Jackie et al. (Sept. 21, 2019). "From Manual Driving to Automated Driving: A Review of 10 Years of AutoUI." In: *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. AutomotiveUI '19: 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications. Utrecht Netherlands: ACM, pp. 70–90. ISBN: 978-1-4503-6884-1. DOI: 10.1145/3342197.3344529. URL: <https://dl.acm.org/doi/10.1145/3342197.3344529> (visited on 12/10/2023) (cit. on p. 1).
- Boyabatli, Onur and Ihsan Sabuncuoglu (2004). "Parameter selection in genetic algorithms." In: *Journal of Systemics, Cybernetics and Informatics* 4.2. Publisher: International Institute of Informatics and Cybernetics, p. 78 (cit. on p. 27).
- Cohen, Jacob (1988). *Statistical power analysis for the behavioral sciences*. 2nd ed. OCLC: 844923079. Hillsdale, N.J.: L. Erlbaum Associates. ISBN: 978-1-134-74270-7 (cit. on p. 47).
- Cohen, Jacob (1992). "A power primer." In: *Psychological Bulletin* 112.1, pp. 155–159. ISSN: 1939-1455, 0033-2909. DOI: 10.1037/0033-2909.112.1.155. URL: <http://doi.apa.org/getdoi.cfm?doi=10.1037/0033-2909.112.1.155> (visited on 12/07/2023) (cit. on p. 47).
- Collendanchise, Michele and Petter Ögren (2019). *Behavior trees in robotics and Al*. Chapman & Hall/CRC artificial intelligence and robotics series 6. Boca Raton: CRC Press/Taylor, Francis Group, CRC Press is an imprint of the Taylor, and Francis Group, an Informa Business. 1 p. ISBN: 978-0-429-48910-5 978-0-429-95089-6 (cit. on pp. 12, 13).

## Bibliography

---

- Dao, Son, Kazem Abhary, and Romeo Marian (Feb. 2016). "Maximising Performance of Genetic Algorithm Solver in Matlab." In: *Engineering Letters* 24 (cit. on pp. 27, 31).
- De Jong, Kenneth (2007). "Parameter Setting in EAs: a 30 Year Perspective." In: *Parameter Setting in Evolutionary Algorithms*. Ed. by Fernando G. Lobo, Cláudio F. Lima, and Zbigniew Michalewicz. Red. by Janusz Kacprzyk. Vol. 54. Series Title: Studies in Computational Intelligence. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 1–18. ISBN: 978-3-540-69431-1 978-3-540-69432-8. DOI: 10.1007/978-3-540-69432-8\_1. URL: [http://link.springer.com/10.1007/978-3-540-69432-8\\_1](http://link.springer.com/10.1007/978-3-540-69432-8_1) (visited on 10/13/2023) (cit. on pp. 7–9, 12, 25, 26, 29, 32).
- De Jong, Kenneth Alan (1975). *An analysis of the behavior of a class of genetic adaptive systems*. University of Michigan (cit. on pp. 9, 27).
- Fazal, M.A. et al. (Mar. 2005). "Estimating groundwater recharge using the SMAR conceptual model calibrated by genetic algorithm." In: *Journal of Hydrology* 303.1, pp. 56–78. ISSN: 00221694. DOI: 10.1016/j.jhydrol.2004.08.017. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0022169404003890> (visited on 10/23/2023) (cit. on p. 27).
- Felbinger, Hermann et al. (Nov. 2019). "Comparing two systematic approaches for testing automated driving functions." In: *2019 IEEE International Conference on Connected Vehicles and Expo (ICCVE)*. 2019 IEEE International Conference on Connected Vehicles and Expo (ICCVE). ISSN: 2378-1297, pp. 1–6. DOI: 10.1109/ICCVE45908.2019.8965209 (cit. on pp. 1, 2).
- Field, Andy P., Jeremy Miles, and Zoë Field (2012). *Discovering statistics using R*. OCLC: ocn760970657. London ; Thousand Oaks, Calif: Sage. 957 pp. ISBN: 978-1-4462-0046-9 978-1-4462-0045-2 (cit. on pp. 38, 39, 41, 42, 46).
- Grefenstette, John (Jan. 1986). "Optimization of Control Parameters for Genetic Algorithms." In: *IEEE Transactions on Systems, Man, and Cybernetics* 16.1, pp. 122–128. ISSN: 0018-9472. DOI: 10.1109/TSMC.1986.289288. URL: <http://ieeexplore.ieee.org/document/4075583/> (visited on 10/13/2023) (cit. on pp. 5, 6, 8–11, 26, 27).
- Hamzaçebi, Coşkun (Mar. 24, 2021). "Taguchi Method as a Robust Design Tool." In: *Quality Control - Intelligent Manufacturing, Robust Design and Charts*. Ed. by Pengzhong Li, Paulo António Rodrigues Pereira, and Helena Navas. IntechOpen. ISBN: 978-1-83962-497-1 978-1-83962-498-8. DOI: 10.5772/intechopen.94908. URL: <https://www.intechopen.com/>

## Bibliography

---

- books/quality-control-intelligent-manufacturing-robust-design-and-charts/taguchi-method-as-a-robust-design-tool (visited on 10/28/2023) (cit. on p. 31).
- Holland, John H. (1992). *Adaptation in Natural and Artificial Systems: An Introductory Analysis with Applications to Biology, Control, and Artificial Intelligence*. The MIT Press. ISBN: 978-0-262-27555-2. DOI: 10.7551/mitpress/1090.001.0001. URL: <https://direct.mit.edu/books/book/2574/adaptation-in-natural-and-artificial-systemsan> (visited on 12/05/2023) (cit. on pp. 5, 6, 9).
- Hussain, Abid and Yousaf Shad Muhammad (Apr. 2020). "Trade-off between exploration and exploitation with genetic algorithm using a novel selection operator." In: *Complex & Intelligent Systems* 6.1, pp. 1–14. ISSN: 2199-4536, 2198-6053. DOI: 10.1007/s40747-019-0102-7. URL: <http://link.springer.com/10.1007/s40747-019-0102-7> (visited on 07/23/2023) (cit. on pp. 6, 7, 9, 12).
- Iovino, Matteo et al. (Aug. 2022). "A survey of Behavior Trees in robotics and AI." In: *Robotics and Autonomous Systems* 154, p. 104096. ISSN: 09218890. DOI: 10.1016/j.robot.2022.104096. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0921889022000513> (visited on 12/05/2023) (cit. on p. 13).
- Jinghui Zhong et al. (2005). "Comparison of Performance between Different Selection Strategies on Simple Genetic Algorithms." In: *International Conference on Computational Intelligence for Modelling, Control and Automation and International Conference on Intelligent Agents, Web Technologies and Internet Commerce (CIMCA-IAWTIC'06)*. International Conference on Computational Intelligence for Modelling, Control and Automation and International Conference on Intelligent Agents, Web Technologies and Internet Commerce (CIMCA-IAWTIC'06). Vol. 2. Vienna, Austria: IEEE, pp. 1115–1121. ISBN: 978-0-7695-2504-4. DOI: 10.1109/CIMCA.2005.1631619. URL: <http://ieeexplore.ieee.org/document/1631619/> (visited on 10/23/2023) (cit. on pp. 9, 27).
- Kalra, Nidhi and Susan M. Paddock (Dec. 2016). "Driving to safety: How many miles of driving would it take to demonstrate autonomous vehicle reliability?" In: *Transportation Research Part A: Policy and Practice* 94, pp. 182–193. ISSN: 09658564. DOI: 10.1016/j.tra.2016.09.010. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0965856416302129> (visited on 12/10/2023) (cit. on p. 1).

## Bibliography

---

- Katoch, Sourabh, Sumit Singh Chauhan, and Vijay Kumar (Feb. 1, 2021). "A review on genetic algorithm: past, present, and future." In: *Multimedia Tools and Applications* 80.5, pp. 8091–8126. ISSN: 1573-7721. DOI: 10.1007/s11042-020-10139-6. URL: <https://doi.org/10.1007/s11042-020-10139-6> (visited on 03/28/2023) (cit. on pp. 5, 7–11).
- Kaufmann, David et al. (Aug. 2021). "Critical and Challenging Scenario Generation based on Automatic Action Behavior Sequence Optimization: 2021 IEEE Autonomous Driving AI Test Challenge Group 108." In: *2021 IEEE International Conference on Artificial Intelligence Testing (AITest)*. 2021 IEEE International Conference on Artificial Intelligence Testing (AITest), pp. 118–127. DOI: 10.1109/AITEST52744.2021.00032 (cit. on p. 2).
- Klampfl, Lorenz, Florian Klück, and Franz Wotawa (2023). "Using genetic algorithms for automating automated lane-keeping system testing." In: *Journal of Software: Evolution and Process* n/a (n/a). \_eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1002/smrv.2520>, e2520. ISSN: 2047-7481. DOI: 10.1002/smrv.2520. URL: <https://onlinelibrary.wiley.com/doi/abs/10.1002/smrv.2520> (visited on 03/29/2023) (cit. on pp. 2, 11).
- Klück, Florian (2022). "Search-based Testing of Automated Driving Systems." PhD thesis (cit. on pp. 1, 2).
- Majumdar, Abhishek and Debasish Ghosh (Oct. 15, 2015). "Genetic Algorithm Parameter Optimization using Taguchi Robust Design for Multi-response Optimization of Experimental and Historical Data." In: *International Journal of Computer Applications* 127.5, pp. 26–32. ISSN: 09758887. DOI: 10.5120/ijca2015906383. URL: <http://www.ijcaonline.org/research/volume127/number5/majumdar-2015-ijca-906383.pdf> (visited on 10/27/2023) (cit. on pp. 5–7, 9).
- Marsili Libelli, S. and P. Alba (July 2000). "Adaptive mutation in genetic algorithms." In: *Soft Computing* 4.2, pp. 76–80. ISSN: 1432-7643. DOI: 10.1007/s005000000042. URL: <http://link.springer.com/10.1007/s005000000042> (visited on 11/21/2023) (cit. on pp. 6, 11, 12).
- Milakis, Dimitris, Bart Van Arem, and Bert Van Wee (July 4, 2017). "Policy and society related implications of automated driving: A review of literature and directions for future research." In: *Journal of Intelligent Transportation Systems* 21.4, pp. 324–348. ISSN: 1547-2450, 1547-2442. DOI: 10.1080/15472450.2017.1291351. URL: <https://www.tandfonline.com/>

## Bibliography

---

- doi/full/10.1080/15472450.2017.1291351 (visited on 12/10/2023) (cit. on p. 1).
- Mills, K. L., J. J. Filliben, and A. L. Haines (June 2015). "Determining Relative Importance and Effective Settings for Genetic Algorithm Control Parameters." In: *Evolutionary Computation* 23.2, pp. 309–342. ISSN: 1063-6560, 1530-9304. DOI: 10.1162/EVCO\_a\_00137. URL: <https://direct.mit.edu/evco/article/23/2/309-342/986> (visited on 10/13/2023) (cit. on pp. 5, 6, 8, 27).
- Naruka, Bhagyashri et al. (July 30, 2019). "Parameter Tuning Method for Genetic Algorithm using Taguchi Orthogonal Array for Non-linear Multi-modal Optimization Problem." In: *International Journal of Recent Technology and Engineering (IJRTE)* 8.2, pp. 2979–2986. ISSN: 22773878. DOI: 10.35940/ijrte.B2711.078219. URL: <https://www.ijrte.org/portfolio-item/B2711078219/> (visited on 10/09/2023) (cit. on pp. 27, 31).
- NazanDanacioglu, F. ZehraMuluk (2005). "TAGUCHI TECHNIQUES FOR  $2^k$  FRACTIONAL FACTORIAL EXPERIMENTS." In: *Journal* 34.1, pp. 83–93. ISSN: 2651-477X-2651-477X (cit. on p. 34).
- Roy, Ranjit K. (1990). *A primer on the Taguchi method*. Competitive manufacturing series. New York: Van Nostrand Reinhold. 247 pp. ISBN: 978-0-442-23729-5 (cit. on pp. 30–32, 34, 35, 39–41, 43, 44).
- SAE International (2021). *SAE J3016 - Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles*. Tech. rep. Visited on 01/07/2022. SAE International. URL: [https://www.sae.org/standards/content/j3016\\_202104](https://www.sae.org/standards/content/j3016_202104). Cit. on pp. 2, 22 (cit. on p. 1).
- Sprague, Christopher Iliffe et al. (Nov. 2018). "Improving the Modularity of AUV Control Systems using Behaviour Trees." In: *2018 IEEE/OES Autonomous Underwater Vehicle Workshop (AUV)*. 2018 IEEE/OES Autonomous Underwater Vehicle Workshop (AUV). ISSN: 2377-6536, pp. 1–6. DOI: 10.1109/AUV.2018.8729810 (cit. on p. 13).
- Srinivas, M. and L.M. Patnaik (June 1994). "Genetic algorithms: a survey." In: *Computer* 27.6, pp. 17–26. ISSN: 0018-9162. DOI: 10.1109/2.294849. URL: <http://ieeexplore.ieee.org/document/294849/> (visited on 10/13/2023) (cit. on pp. 5, 7, 8, 10–12, 27).
- Taguchi, Genichi et al. (2005). *Taguchi's quality engineering handbook*. Hoboken, N.J. : Livonia, Mich: John Wiley & Sons ; ASI Consulting Group. 1662 pp. ISBN: 978-0-471-41334-9 (cit. on p. 35).

## Bibliography

---

- University Malaysia of Computer Science and Engineering et al. (Feb. 2017). "Crossover and Mutation Operators of Genetic Algorithms." In: *International Journal of Machine Learning and Computing* 7.1, pp. 9–12. ISSN: 20103700. DOI: 10.18178/ijmlc.2017.7.1.611. URL: <http://www.ijmlc.org/index.php?m=content&c=index&a=show&catid=69&id=704> (visited on 12/15/2023) (cit. on p. 10).
- Whitley, Darrell (June 1, 1994). "A genetic algorithm tutorial." In: *Statistics and Computing* 4.2, pp. 65–85. ISSN: 1573-1375. DOI: 10.1007/BF00175354. URL: <https://doi.org/10.1007/BF00175354> (visited on 03/28/2023) (cit. on p. 27).
- Xia, Xuemin et al. (Feb. 1, 2019). "Genetic algorithm hyper-parameter optimization using Taguchi design for groundwater pollution source identification." In: *Water Supply* 19.1, pp. 137–146. ISSN: 1606-9749, 1607-0798. DOI: 10.2166/ws.2018.059. URL: <https://iwaponline.com/ws/article/19/1/137/39199/Genetic-algorithm-hyperparameter-optimization> (visited on 10/06/2023) (cit. on p. 5).
- Yang, Kai and Basem El-Haik (2009). *Design for six sigma: a roadmap for product development*. 2nd ed. London: McGraw-Hill [distributor]. 741 pp. ISBN: 978-0-07-154767-3 (cit. on pp. 29–35, 37, 40, 41).

# **Appendix**



# Appendix A.

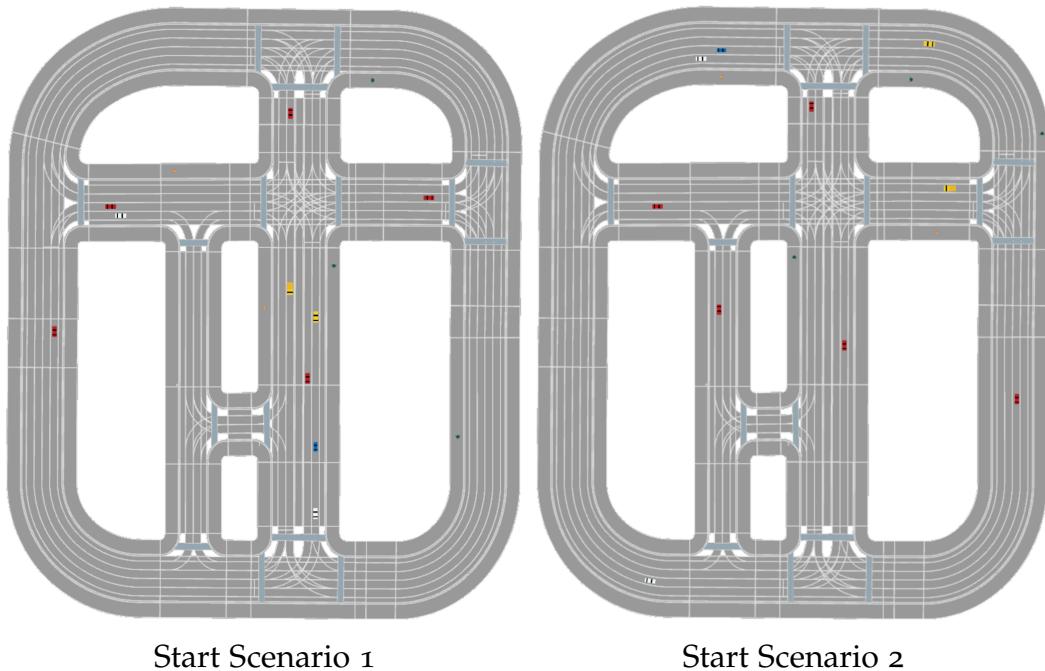


Figure 1: Start Scenarios

## Appendix A.

---

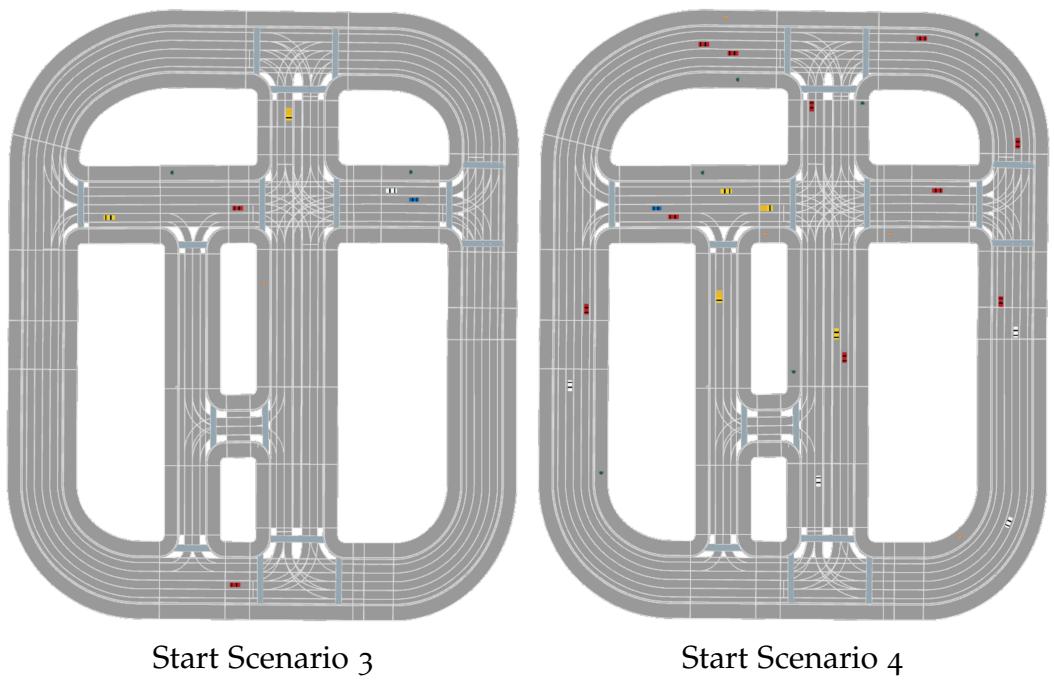


Figure 2: Start Scenarios

## Appendix B.

NO.	rep1	rep2	rep3	rep4	rep5	rep6	rep7	rep8
1	3.76	3.90	4.75	4.23	4.32	5.75	3.94	3.95
2	8.06	5.20	4.75	5.04	4.63	5.79	4.32	6.00
3	8.62	7.89	8.76	6.44	8.77	6.68	5.96	7.22
4	7.65	6.95	6.49	5.35	6.24	7.97	6.52	6.42
5	4.26	5.45	4.55	4.20	3.80	5.29	6.05	7.02
6	5.26	5.21	5.71	5.59	5.48	5.64	3.61	5.47
7	3.92	4.01	4.51	4.80	4.08	4.43	4.10	6.05
8	6.60	5.69	5.79	5.79	5.43	5.03	6.11	6.05
9	4.93	5.05	5.17	4.91	6.53	5.04	7.66	5.73
10	5.84	6.72	4.87	7.13	6.82	5.74	4.66	6.78
11	4.93	6.21	4.10	4.67	5.94	5.19	3.91	3.96
12	5.54	4.84	7.10	5.83	5.96	5.17	6.02	8.94
13	11.22	7.88	5.94	7.00	5.88	7.05	6.40	6.66
14	6.05	7.40	7.50	6.51	9.58	5.03	5.35	5.09
15	6.58	4.35	4.50	7.21	6.38	5.77	5.45	6.08
16	4.35	6.66	8.57	4.44	4.49	4.89	6.72	5.37

Table 1: Hyperparameter Tuning: Taguchi Experiment Results

---

## Appendix B.

scenario	rep1	rep2	rep3	rep4	rep5	rep6	rep7	rep8	rep9	rep10
1	7.28	7.31	9.09	9.38	8.16	8.05	7.69	10.20	9.22	8.83
2	7.76	9.42	8.28	9.51	9.96	10.27	10.38	8.87	9.82	8.12
3	7.67	7.34	6.86	4.86	5.00	7.14	8.33	5.51	6.18	7.66
4	10.19	11.57	10.67	10.71	9.07	11.25	10.19	10.09	12.29	9.97

Table 2: Evaluation Results Optimized

scenario	rep1	rep2	rep3	rep4	rep5	rep6	rep7	rep8	rep9	rep10
1	6.66	6.10	6.32	7.32	7.37	9.23	6.44	8.57	6.14	6.70
2	7.09	6.78	7.00	7.10	6.01	8.04	6.75	8.59	9.13	8.12
3	8.31	6.14	6.94	8.99	5.27	4.94	6.56	6.03	6.61	5.11
4	8.78	9.44	8.22	7.47	7.99	9.58	9.45	8.59	6.90	8.17

Table 3: Evaluation Results Default

scenario	rep1	rep2	rep3	rep4	rep5	rep6	rep7	rep8	rep9	rep10
1	3.92	4.41	4.19	4.33	4.38	4.88	8.27	4.76	5.65	4.64
2	5.16	4.91	4.82	4.89	4.91	5.47	4.97	6.21	4.93	4.99
3	4.53	4.63	4.35	4.62	4.13	4.14	4.91	5.98	4.56	4.34
4	7.01	6.01	6.63	7.31	6.85	6.66	7.35	6.78	7.38	6.57

Table 4: Evaluation Results Random